

Temperatures and shelf-life duration in the strawberry supply chain

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Abstract

Strawberry is a very perishable fruit that requires proper temperature management to reduce losses. Temperature abuses in the strawberry supply chain leads to high losses and dissatisfaction on the part of consumers and retailers. The temperature was monitored in two commercial circuits from harvesting to the final consumer, in June and July of 2016. Temperatures outside and inside of 500 g clamshells and inside the fruits were recorded in the three locations of the pallet. The air temperature inside 5 vehicles trunks and 5 domestic refrigerators were recorded at 60 seconds intervals. Strawberry (*Fragaria xananassa*) packaged in clamshells were stored at 0, 5, 10, 15, and 20 °C. Fruit were evaluated for colour, firmness, soluble solids content (SSC), and titratable acidity (TA). A 10-member panel assessed the fruit for odour, texture, juiciness, flavour, and overall liking at the same sampling dates. In the studied circuits fruits were exposed to an accumulated time-temperature (ATT) of 502.3 and 588.8 °C h. In both the display in store represented the largest contribution to the ATT (273.1 and 281.2 °C h). The maximum temperatures recorded in trunks each day were 47.3, 40.3, 41.4 and 48.2 °C with an outdoor temperature of 24.0, 26.1, 28.2 and 36.6 °C. In refrigerators were recorded average temperatures of 7.2, 4.3, 9.2, 7.4 and 7.7 °C with reaching temperature fluctuations higher than 5 °C. The temperature had little effect on the physicochemical characteristics and sensory evaluation of the strawberry, but strongly influenced the evolution of the losses. The clamshells have become unmarketable after 3 days at 20 °C and 5 days at 15 °C. Damages development can arise in the retail or just in consumers houses with the 'last mile' temperatures being possibly the responsible for the biggest quality depreciation on strawberries.

Keywords: 'Last mile', Quality, Strawberry, Supply chain, Temperature.

Resumo

A morango é um fruto muito perecível que requer uma gestão adequada da temperatura de modo a reduzir as perdas. Abusos de temperatura na cadeia de abastecimento do morango leva a grandes perdas e insatisfação por parte dos consumidores e retalhistas. A temperatura foi monitorizada em dois circuitos comerciais desde a colheita até ao consumidor final, em junho e julho de 2016. As temperaturas dentro e fora de cufetes de 500 g e dentro dos frutos foram registradas nos três locais da paleta. A temperatura do ar dentro de 5 bagageiras de veículos e 5 frigoríficos domésticos foi registada em intervalos de 60 segundos. O morango (*Fragaria* x *ananassa*) embalado em cufetes foi armazenada a 0, 5, 10, 15 e 20 ° C. Os frutos foram avaliados quanto à cor, firmeza, teor de sólidos solúveis (SSC) e acidez titulável (TA). Um painel de 10 membros avaliou os frutos quanto ao odor, textura, suculência, sabor e apreciação global nas mesmas datas de amostragem. Nos circuitos estudados os frutos foram expostos a um tempo-temperatura acumulado (ATT) de 502,3 e 588,8 ° C h. Em ambos, a exibição em loja representou a maior contribuição para a ATT (273,1 e 281,2 ° C h). As temperaturas máximas registradas em bagageiras por dia foram 47,3, 40,3, 41,4 e 48,2 ° C com temperaturas exteriores de 24,0, 26,1, 28,2 e 36,6 ° C. Nos frigoríficos foram registradas temperaturas médias de 7,2, 4,3, 9,2, 7,4 e 7,7 ° C com flutuações de temperatura atingindo mais de 5 ° C. A temperatura teve pouco efeito sobre as características físico-químicas e a avaliação sensorial do morango, mas influenciou fortemente a evolução das perdas. As cufetes tornaram-se não comercializáveis após 3 dias a 20 ° C e 5 dias a 15 ° C. O desenvolvimento de danos pode surgir nas lojas ou apenas em casas de consumidores com as temperaturas do "último quilómetro" sendo possivelmente o responsável pela maior depreciação de qualidade em morangos.

Resumo extendido

O morango é um fruto muito perecível que tem de percorrer a cadeia de abastecimento, entre a colheita e o consumo, em cerca de uma semana em condições ótimas que raramente se verificam nas operações reais. A temperatura ótima para a conservação do morango é 0 °C. A longevidade pós-colheita reduz-se significativamente com uma inadequada gestão da cadeia de frio, nomeadamente o aumento da temperatura e os atrasos no arrefecimento após a colheita. Os excessos de temperatura na cadeia de abastecimento do morango conduzem a elevadas perdas e insatisfação, motivando muitas reclamações por parte de consumidores e retalhistas. A cadeia de abastecimento é uma série de processos, operações e entidades que ligam produtores, grossistas, retalhistas e consumidores, em conjunto com fornecedores de fatores de produção, prestadores de serviços e outras partes interessadas que leva os alimentos do seu estado natural até ao prato dos consumidores. O «último quilómetro» das cadeias de abastecimento é a fase final, onde a cadeia se dispersa por um grande número de pontos de venda que, por sua vez, se multiplicam no abastecimento a milhares de consumidores. O «último quilómetro» compreende as etapas desde que os frutos são adquiridos pelo consumidor, compreendendo o transporte e armazenamento doméstico. As temperaturas a que os frutos são sujeitos e as quebras da cadeia de frio que ocorrem nesta última fase não se encontram quantificadas de forma a permitir avaliar as consequências e permitir tomadas de decisão de gestão adequadas. Um dos problemas do «último quilómetro» da pós-colheita hortofrutícola consiste na dificuldade de controlar a temperatura quando os produtos estão na posse do consumidor. Os automóveis destes não são refrigerados e não se utilizam sacos isotérmicos no transporte de fruta refrigerada até casa. Os frigoríficos, eletrodomésticos não permitem um controlo da temperatura de conservação e têm regimes de funcionamento e capacidade de manutenção da temperatura muito variáveis.

Os objetivos deste estudo foram: (1) avaliar as alterações sensoriais e físico-químicas do morango como consequência da temperatura de armazenamento de forma a melhorar a gestão da cadeia de abastecimento; (2) tipificar as causas de perdas de morango a nível do retalho; (3) quantificar a evolução dessas causas durante a vida de prateleira; (4) avaliar as condições ambientais durante toda a cadeia de abastecimento, desde a colheita até casa do consumidor; (5) e as consequências das temperaturas no "último quilómetro", em particular, em bagageiras de carros e frigoríficos domésticos.

A temperatura foi monitorizada em dois circuitos comerciais, de dois fornecedores distintos, desde a colheita até o consumidor final, em junho e julho de 2016. As temperaturas fora e dentro de cuvetes de 500 g e no interior dos frutos foram monitorizadas em três locais da paleta, topo, meio e base. A temperatura do ar foi monitorizada em intervalos de 60 segundos

no interior de bagageiras de 5 veículos e de 5 frigoríficos domésticos. Morango (*Fragaria x ananassa*) embalados em cusetes de 500 g foram armazenados a 0, 5, 10, 15, e 20 °C e analisados ao fim de 3, 5, 7, 10, 12 e 14 dias. Os frutos foram avaliados quanto à cor, firmeza, teor de sólidos solúveis (SST) e acidez titulável (AT). Um painel de 10 membros avaliaram os frutos quanto ao odor, textura, suculência, flavor e apreciação global, numa escala de 1 a 5.

Num dos circuitos, até à entrega no entreposto foram registadas na polpa temperaturas máxima, média e mínima de 27,7, 4,5 e 0,7 °C, respetivamente. No outro circuito, os valores foram, respetivamente, de 35,1, 14,8 e 5,1 °C. Os frutos foram expostos a uma temperatura acumulada de 502,3 e de 588,8 °C h em cada um dos circuitos estudados. Em ambos os circuitos a disposição dos frutos em loja representou a maior contribuição para a temperatura acumulada (273,1 e 281,2 °C h), representando cerca de metade do valor total. Circuito 1 decorreu durante aproximadamente 7 dias e teve uma ATT total de 1172,2 °C h que pode ter levado a uma percentagem de frutos com danos de 42%. Circuito 2 decorreu apenas cerca de 5 dias e teve uma ATT de 941,4 °C h levando a uma estimativa de 35,8% de frutos com danos. Embora tenha havido uma diferença de quase dois dias entre os circuitos ambos levam a estimativas semelhantes de frutos danificados, o que indica que o circuito 2 foi menos eficiente em termos de gestão da temperatura.

As bagageiras atingiram valores de temperatura 20 °C superiores à temperatura exterior e valores absolutos próximos dos 50 °C. As oscilações da temperatura nas bagageiras seguiram o mesmo padrão em todos os veículos, mas com amplitudes diferentes. Veículos estacionados em garagens apresentaram temperaturas inferiores em cerca de 10 °C quando comparado com os que se encontravam estacionados no exterior. A temperatura máxima do ar das bagageiras durante o período do estudo foi registada no dia 3 de julho com um valor de 48,2 °C. Uma vez que a temperatura do ar em Lisboa nesse momento foi de 36,6 °C, o interior do porta-bagagens atingiu uma temperatura 11,6 °C acima da temperatura exterior. Nos outros dias a temperatura máxima atingida nas bagageiras foi de 47,3; 40,3 e 41,4 °C, nos dias 1, 2 e 3, com uma temperatura máxima registada segundo o IPMA de 24; 26,1 e 28,2 °C, respetivamente. Um dos frigoríficos analisados, com apenas 6 meses de utilização, apresentou ciclos de arrefecimento inferiores a uma hora, com amplitudes inferiores a 0,5 °C e temperatura compreendidas entre 7,0 e 7,5 °C. Os restantes oscilaram em ciclos de 2 a 3 horas com amplitudes de 1,5 a 3,0 °C, mas não mantiveram a temperatura em torno de um valor médio constante. Os restantes frigoríficos não apresentaram ciclos frigoríficos regulares, sendo evidentes vários picos de temperatura relacionados com a abertura da porta por parte dos utilizadores. Foram registradas oscilações de 5,2; 2,5; 4,3; 2,1 e 4,5 °C nos frigoríficos. Essas oscilações são suscetíveis de causar condensação no interior de embalagens o que pode favorecer o desenvolvimento de bolores.

As cuvetes analisadas tornaram-se não comercializáveis após armazenadas 3 dias a 20 °C e 5 dias a 15 °C. Os fatores determinantes da qualidade do morango na cadeia de abastecimento são os danos mecânicos e as infecções patológicas, que se expressam rapidamente mesmo que não sejam evidentes após a colheita. As características físico-químicas e sensoriais ficam, no essencial, determinadas no momento da colheita e os efeitos da sua subsequente evolução pós-colheita não se sobrepõe, do ponto de vista de gestão integral da qualidade na cadeia, aos efeitos provocados pelos danos mecânicos e pelas podridões. A rápida evolução das perdas a temperaturas superiores a 0 °C mostra que a gestão da temperatura é fundamental, mesmo no final da cadeia de abastecimento ao nível do retalho e do consumidor. A análise das causas e a evolução dos sintomas das perdas revela que as características iniciais, as infecções latentes, o nível de inóculo e os danos mecânicos na colheita, acondicionamento e transporte são determinantes da satisfação de retalhistas e consumidores. A temperatura representa um peso superior sobre o desenvolvimento de danos do que o tempo de armazenamento, com os retalhistas a poderem aumentar o tempo de venda ou a qualidade potencial no momento de venda em 3 vezes se optarem pela exposição refrigerada em detrimento da temperatura ambiente. A velocidade de manifestação das pisaduras e podridões faz com estes danos latentes possam facilmente surgir no retalho ou em casa dos consumidores mesmo que os lotes estivessem isentos de danos visíveis à saída da central.

Palavras-chave: Cadeia de abastecimento, Morango, Qualidade, Temperatura, «Último quilómetro».

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Abbreviations

ATT - Accumulated time-temperature

C* - Chroma

EU28 - European Union 28 members

FAO - Food and Agriculture Organization

H° - Hue degree

INE - Instituto Nacional de Estatística

IPMA - Instituto Português do Mar e da Atmosfera

L* - Lightness

PET - Polyethylene terephthalate

SSC - Soluble Solid Content

TA - Titratable Acidity

TCSC - Temperature Controlled Supply Chain

TIF - Transportes Ideal da Freixeira (transportation subcontracted company)

TT - Time-temperature

WHO - World Health Organization

Wi - Initial weight

Wt - final weight

Introduction

For many years the fruits and vegetables market was dependent on the seasonality of the products and their perishability. The development that occurred on the last decades on the supply chains allowed products to be transported in refrigerated environments and made possible for fruits and vegetables to travel all over the world, while maintaining their quality.

Consumers demand for quality products increased considerably and they are not willing to pay or consume products with bad appearance and even slightly damaged, which has led to heavy losses that occur in stores and at their homes every day. This problem has led to the involvement of retailers and world organizations in order to improve supply chains, storage and display conditions and consumer awareness in order to improve product quality and reduce food waste.

Strawberry is one of the most perishable fruit in the market being the main focus of complaints by retailers and consumers. Strawberry losses that occur at the retailer and consumer level are not quantified. However, information gathered from the distribution operators, not empirically confirmed, indicate that the strawberry is the fruit with the highest proportion of breaks in modern distribution. The management of temperature in the whole supply chain is the determining factor.

Although optimal storage temperature to preserve strawberry is 0 °C, in the Portuguese retail stores these are often found at room temperature, instead of the British market where strawberries are mostly found in refrigerated displays. Shelf life at 0 °C is up to 7 days (Mitcham, 2004), and it is shorter at higher temperature.

It is undeniable that the cooling conditions are the key to good management of strawberry postharvest quality. However, if the logistical level there is no doubt about the proper management of temperature (Mitchell et al., 1996) - that does not mean that the recommendations are adopted rigorously - since at the exposure level on the point of sale a dilemma arises. In store if exposed to room temperature (eg, 20-22 °C) is increased the emission of volatile aroma compounds from the fruit which leads to a higher perception of odor by the consumer promoting impulse sale, while refrigerated display (2 to 4 °C) allows the maintenance of strawberries quality, but restricts the aroma released and therefore impulse buying.

The objectives of the studies reported herein were: (1) To evaluate the sensory and physicochemical changes of strawberry as affected by temperature to improve supply chain management; (2) Typify the causes of losses of strawberry at the retail level; (3) Quantify the evolution of these causes during shelf life; (4) Evaluate the environmental conditions during the whole supply chain, from harvest to consumer household and (5) The consequences of the temperatures in the 'last mile', in particular, in cars trunks and domestic refrigerators.

Literature Review

Food supply chain

Food supply chains are a series of processes, operations and entities linking suppliers, manufacturers, freight service providers, retailers, and consumers, along with other stakeholders, that take the food from its raw material state to the consumer's plates (Dani, 2015; Nagurney & Li, 2016). Supply chain management is essential since the consumers are increasingly demanding and food needs to be available at the right time, right quality and right quantity (Dani, 2015), reaching a high level of complexity in international supply chains. A typical food supply chain and its stages are represented in Figure 1.

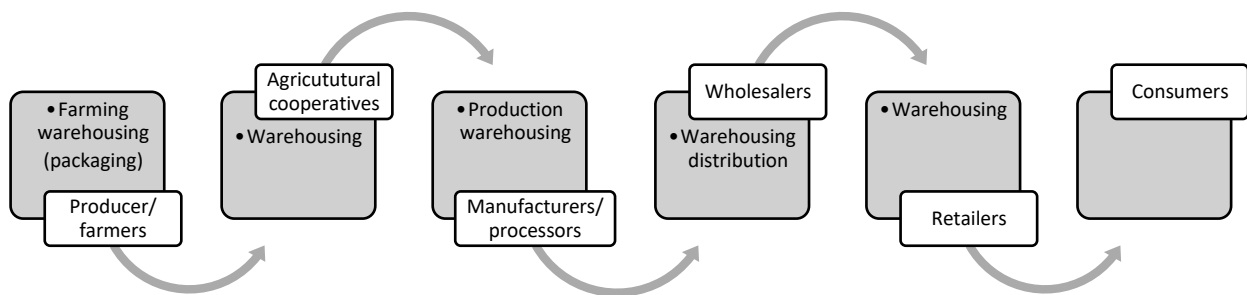


Figure 1 - Typical food supply chain (adapted from Lakovou et al., 2016).

Modern food supply chains must take into account quality, technology, information technology, regulatory framework, logistics, and consumer behavior (Bourlakis & Weightman, 2004).

Logistics is a key component of supply chain management. Logistics is « the operational component of supply chain management, including quantification, procurement, inventory management, transportation and fleet management, as well as data collection and reporting. » (Dani, 2015). Logistic is highly dependent on the information technology systems (Dani, 2015) and have becomes more challenging when all the supply chain needs controlled temperature (Bourlakis & Weightman, 2004).

Temperature controlled supply chain

Some food products need to be maintain in a constant cold environment to maintain its quality and safety to the consumer (Brenner, 2015) during a reasonable shelf life period to ensure proper functioning of the supply chain (Bourlakis & Weightman, 2004). A supply chain operated under refrigerated conditions is called a «cold chain» or, more generally, a temperature controlled supply chain (TCSC).

A TCSC is a specific food supply chain where the products need to be maintained at low temperatures throughout the different stages. Though this is a complex and expensive process due to the length and the dedicated distributions facilities and equipment's to control temperature from the producer to the consumer (Bourlakis & Weightman, 2004; Dani, 2015).

There has been an intensification in the investment on the cool supply chains. Given the large capital investments and operating expenses required for cold storage and transportation, there is growing need for articulation among the cool chain stakeholders, which requires a common understanding of the whole cold chain challenges (Cool Chain Europe, 2016)

Cold chains operate at different temperature levels according to the product group. Frozen foods require -25 °C for ice creams, cold chill temperatures for fresh meat, dairy and some fruits and vegetables needing 0°C to +1°C, medium chill temperatures for pastry, butter and cheese requiring +5°C and exotic chill temperatures demanding +10°C to +15°C for potatoes, eggs, exotic fruits and bananas. That leads to a more complex process when products with different necessities and characteristics need to be transported together (Bourlakis & Weightman, 2004). The multi-temperature vehicles can be a solution for mixed loads, when products with different temperature requirements need to share storage or transportation space (Dani, 2015).

According to Dani (2005) there are 6 factors to take into account when designing supply chain for perishable products that need controlled temperature:

1. Guarantee that the temperature required for the specific product can be maintained throughout the entire supply chain;
2. Type of transportation used should be decided according to the cost and shelf life of the product;
3. Food safety must be controlled, traceability guaranteed, and the regulatory requirements applied.
4. Packaging where the product will be transported should minimize the exposure and increase shelf life;
5. Monitoring of temperature, movement, location, humidity and other relevant parameters of the product, if possible in real time, and use the data for analysis and future improvements;
6. Understand the dynamics of the cold chain and assure an effective on-cost and on-time delivery.

This type of supply chains has specific requirements regarding the strategy behind collaborative logistics projects; failure in implement a collaborative strategy are a barrier to successful supply chain operation (Lakovou, et al., 2016).

Production

The fruit supply chain starts at the farm, the organization that assures primary production of fresh fruit produce from the crop. Farms can be a family-owned and run business or be incorporated as small to large corporations.

The agricultural sector maintains the food availability and the sustainability for the population and the economy (Dani, 2015). Therefore, it is specific of every country or region. The Portuguese farming sector is undergoing fast changes. From 1989 to 2005 the number of agricultural holding in Portugal decreased by 46%, yet the average size of these holding increased by 70% (INE, 2007). The average size of the agricultural holdings in Portugal are very similar to the EU28 with 13.8 and 14.4 hectares by farm, respectively. In addition, 46.2% of these farms have less than 2 hectares. These farms are managed by older farmers when compared to the EU28 average with 50% of the owners 65 years old or more in contrast to the 29% of EU28 (Alves, 2014; Eurostat, 2016). However, there has been an increase of qualified people who dedicate to agriculture from 1.8% to 3.2% of the total of producers from 1995 to 2005 (INE, 2007). The population dedicated to the agricultural sector in Portugal its only 2.8% of the total employed population (INE, 2015b).

These structural characteristics of the farming sector in Portugal determine, in part, the structure of supply chains of fruit and vegetables, and their response to the pull driven major operators, such as the modern retailing sector.

Fresh fruit sector in Portugal

The consumption of fresh fruit decreased throughout the past years but are presenting a small increase rate since 2013 (fig. 2). The food retail companies are making some effort in order to improve the quality of these product and incentive people to buy by appealing with publicity on television and weekly promotional flyers.

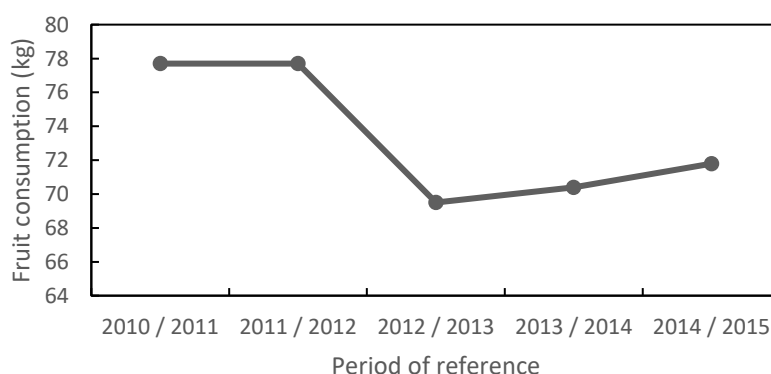


Figure 2 - Evolution of per capita fresh fruit consumption in Portugal 2010 to 2015 (INE, 2015a).

The Portuguese market regarding to supply balances of fresh fruit had 76.8% auto provisioning capacity (2013/2014), below of the internal needs that must be met by imported fruit (INE, 2015a). Table 1 presents the internal consumption of fruits and of the most marketed fruit types.

Table 1 - Internal consumption of fruit in 2014 (adapted from INE, 2015b).

Item	Internal consumption	Proportion of total
Total of fruits	1,175,000 t	100%
Apples	305,000 t	26%
Citric fruit	196,000 t	17%
Pears	99,000 t	8%
Peaches	71,000 t	6%
Table grapes	57,000 t	5%

There a few fundamental drivers for fruit and vegetable consumption that require responses from the supply chain. The low consumption of fruits and vegetables is commonly associated with obesity (WHO, 2016). A reduced risk of mortality from all causes, particularly cardiovascular diseases, can be archived with an increase consumption of fruits and vegetables (Wang, et al., 2014). However according to the WHO an estimated 5.2 million deaths worldwide in 2013 could have been prevented by increasing the fruits and vegetables consumption (Anon, 2016).

Fruits and vegetables are commonly associated with health and good eating habits. The Portuguese market however has still a lot of space to grow since their consumption remains below the WHO recommendation with only 72% of the Portuguese population consuming fruits and 55% vegetables on a daily base (INE, 2016). The WHO suggest people to eat at least 400 grams of fruits and vegetables per day to improve their overall health (Anon, 2016) and has developed in 1988 a worldwide campaign “5 a day” with the goal of improving the consumption of fruits and vegetables for at least 5 servings a day (WHO, 2003).

Pre-cooling and storage

The fruit sector handles products that start losing value immediately after harvest (Dani, 2015). The removal of field heat as soon as possible is essential to maintain the quality and product shelf life (Welby & McGregor, 2004). Every product that is going through the cold chain should be precooled before placed at the storage temperature (Almeida, 2005). The removal of field heat can be done in normal storage rooms but has numerous advantages when held in a rapid

cooling chamber. The precooling requires increased power and air flow rate in order to remove the heat in a faster way than what a cold room can supply (Almeida, 2005).

The precooling can help extend the product life by reducing the respiration rate, the rate of ripening, the moisture loss, the ethylene production and the spread of decay. The success of this step depends on: the time between harvest and precooling; the type of shipping container; the use and type of packaging; the initial temperature of the product; the velocity or amount of cold air, water or ice; the temperature desired; the sanitation of the air or water and the maintenance of the temperature of the product before (Welby & McGregor, 2004).

To meet with consumer requirements there has been an increasing investment on long-term storage facilities since they can add value to products by increasing their selling life and allowing to have some products available off season (Williams, 2014). However, the storage of perishable products evolves costs, so the consumer need to value this cost on the product to obtain return on the investment (Williams, 2014).

Transportation

Transport is a key element on the supply chain, connecting different stages and allowing the product to go from the producer to the consumer. Transportation is associated to high costs that may represent a large share of the total supply costs and one of the main sources of quality depreciation (Almeida, 2005). However, moving products from one place to another is warranted whenever it adds values, as happens with every logistic operation.

The most frequent problems found during transportation are associated with the displacement of the load and the compression of the products. Vibrational damages, mishandling, and waiting times under non-refrigerated conditions on the loading dock can also lead to high quality or even commercial losses. However, the lack of temperature control is what leads to the biggest quality problems during fruit and vegetable transportation. The refrigerated transportation equipment should not be used to remove field heat since it does not have the refrigeration capacity to cool down products (Welby & McGregor, 2004; Almeida, 2005).

When loading the products for transport it is important to guarantee that they can be mixed and are compatible. Further challenges arise when transporting fruit and vegetables that can have negative effects on each other (Brenner, 2015). The recommended temperature and relative humidity, the production and sensitivity to ethylene and the production and absorption of odors are characteristics that need to be taken in account when preparing a load to ship (Welby & McGregor, 2004; Almeida, 2005).

It is crucial to maintain optimal temperature conditions during transportation but also the frequency and extend of temperature deviations encountered in transit should be taken in account (Brenner, 2015). When choosing the type of equipment, the follow factors must be considered: the destination; the value of the product; the degree of perishability; the volume transported; the temperature and humidity recommended; the exterior temperature throughout the transport; time in transit to reach destination by air, land or ocean transport; freight rates negotiated with the carriers and the quality of the service (Welby & McGregor, 2004).

Warehouse

A warehouse is a temporary place where products are stored and dispatched as quickly, effectively and efficiently as possible to reach the stores in a timely and cost-effective manner (Richards, 2014). Large retailers have their own distribution centers where producers deliver the products and then are distributed to individual retail stores (Dani, 2015). Usually these facilities are located near industrial centers, urban areas and nearby major transport routes (Zajac, 2016).

Warehouses represent an average 22% of the total logistics costs to the companies. When managing products that need to be maintain refrigerated the demand of energy is enormous as the costs associated (Zajac, 2016).

Nowadays the retail companies are investing on the quality of fresh products and most retailers do not have stocks of fruits and vegetables overnight. The current trend is to move the products from warehouses as faster as possible, optimizing the warehouse managing (Gustafsson, et al., 2006).

Store

The final selling point is where the consumer meets the fruit handled by the supply chain. Various types of outlets can fulfil this role in a supply chain, but in developed countries a large percentage of fruit are sold to the consumer in retail stores from modern distribution companies that operate a large number of stores in one or various countries.

An attractive produce department is regarded by many retailers as the best way to give a positive quality image of their stores. Fruit and vegetable sensory attributes, such as color, texture, and aroma are easily perceived by the consumers and significantly affect their purchase decision. Some fresh products as fruit and vegetables need to be in a refrigerated displayer in order to maintain their quality.

Fruits and vegetables are often handled under adverse environmental conditions, resulting in produce with poor quality and shorter shelf life, and increased waste at the retail and consumer levels.

'Last mile'

'Last mile' is the stage between store and the consumer domestic refrigerator. While the stages of the supply chains from the producer until the product gets to the store has been the focus of a lot of studies, the path that the fruits take after being purchased is still understudied.

Even though all intervenient of the supply chain are able to maintain the fruits under constant temperature problems can occur in the 'last mile'. The biggest problem of the 'last mile' of fruit and vegetable is the difficulty to control the temperature when the products are in consumer's hands.

Consumer's cars are not refrigerated and most do not use insulated bags to transport the fruits home. In the Summer temperatures can get very high and in most trunks the temperature can reach values of 50 °C leading to possible deterioration of the fruits compromising the entire effort made until then.

Refrigerators and appliances that allow to control fruit and vegetables storage temperature at the end of 'last mile', have operating systems and temperature control capabilities that vary widely. The consumer does not have the capacity to control the temperature in a precise way inside the refrigerator, neither has (in the great majority of the cases) a display to know the temperature at which the refrigerator is in that moment.

Strawberry: Postharvest handling and quality

Strawberry was chosen to address the supply chain temperature effects on quality and losses. This sections, reviews and summarizes the major issues related to postharvest strawberry handling and quality.

Strawberry temperature and relative humidity play the biggest role when addressing to quality and deterioration control. The temperature management can control ripening, softening, textural and color changes, moisture loss, and spoilage due to fungal invasion (Hardenburg et al., 1986). Changes in color and development of visible decay are the main causes of changes in strawberry visual quality. Being these characteristics evolution dependent on increased time and temperature (Nunes, 2008).

Fruit morphology

Strawberry, *Fragaria x ananassa*, belongs to the Rosaceae family. Although commonly being referred as a fruit, strawberry is derived from receptacle containing multiple achenes (the actual botanical fruit). However, from the standpoint of ripening and postharvest behavior, the strawberry receptacle behaves like an actual fleshy fruit (Mitcham, 2014). According to Szczesniak and Smith (1969) the strawberry has 5 tissue zones: Epidermis, consisting of polygonal cells and long, pointed, thick-walled hairs; hypodermis, composed of meristematic cells with no intercellular spaces; cortex or true flesh, consisting of rounded cells with intercellular spaces; bundle zone, comprising spiral and annular vessels; and the pith, consisting of thin-walled cells which often separate during the growth of the berry leaving large cavities.

Optimum handling conditions

Strawberries should be ideally stored at $0 \pm 0.5^{\circ}\text{C}$ with 90 to 95% relative humidity in order to reduce the produce deterioration rate and raise the potential market life (Mitcham et al., 1996).

It is essential to pre-cool the fruits as fast as possible after harvest by removing the field heat. The marketability can be extremely reduced with the cooling delay (fig. 3). The pre-cooling should be done by forced-air cooling although sometimes the fruits are placed in room-cooling (Mitchell et al., 1996). The reduce of marketability is mainly due to decay, weight loss, changes in color, decreased firmness and soluble solid content (Nunes et al., 1995). The incidence and severity of decay, mainly caused by *Botrytis cinerea* and *Rhizopus stolonifera*, can be reduced by 25% and 24%, respectively if the fruits are properly pre-cooled (Nunes et al., 2005).

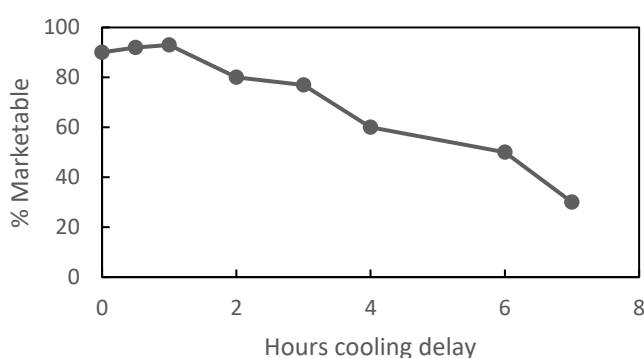


Figure 3 - Effect on cooling delay after harvest on the marketability of strawberries (redrawn from Mitcham et al., 1996).

If stored at 0°C fruits can be kept for 7 to 10 days with good quality. When exposed to higher temperatures the exposure time and the temperature raise are both relevant to the possible deterioration (Kader, 2002). A 10°C raise on the temperature can increase two to four folds

the rate of deterioration (Mitchell et al., 1996) as the respiration rate increases and the sugars and acids decrease (Moraga et al., 2006). According to Shin et al. (2007) fruits stored for a short period of time, 4 days, can be kept at 10°C with no significant difference on the fruits quality.

It is essential to keep the temperature as closed to 0 °C throughout the whole supply chain and minimize temperature fluctuations that can lead to water condensation. In order to reduce the water loss and condensations, the relative humidity should be maintained as closed to 90 to 95% as possible. The condensations can enhance the expression of bruising, increase weight loss and accelerate decay. Whenever compromises are required, it is better to expose the fruits to optimal temperature only at some stages of the chain than maintaining the fruits at a higher and constant temperature (Nunes et al., 2003).

Losses throughout the strawberry supply chain

The control of food waste is an issue that concerns more and more people and institutions worldwide. Close to one-third of food produced for human consumption is wasted every year, in the fruits and vegetables chain more than 40% is wasted (Sonesson & Meybeck, 2011).

Good management of the entire supply chain is crucial, but challenging. Sometimes growers have peaks of production that the market cannot absorb generating high volumes of waste. Selling point promotions are used to drive demand, and can raise the sales for up to 50%, although retail companies may not be able to organize promotions quickly enough to respond to surpluses. Planning fruit production is therefore fundamental to meet with the demand (Terry et al., 2011).

According to Terry et al. (2011), strawberry waste occurs mainly due to disease, physical breakdown and handling, with varietal selection, adequate temperature and relative humidity management being crucial to reduce waste.

A survey in the United Kingdom revealed that strawberry losses in the supply chain occur mainly at harvest, reaching 20% of the entire production (Terry et al., 2011). Undersized and diseased berries; varietal selection; inadequate removal of field heat; and high temperature and relative humidity are the main causes of field loss and waste. Hot weather tends to increase the percentage of fruits in the field that become darker and are more prone to bruising, which can lead to an increased waste in the field or in later stages of the supply chain. A big problem are the fruits that have no market, as class II fruits or damaged fruits, who are not always picked up leading to an increased level of pathogen load in the field and therefore an increase disease incidence in the remaining fruits (Terry et al., 2011).

After harvested the strawberries are usually transported to the packing house where they are cooled and stored until shipped. At these stages the waste was estimated at 3% with the main causes of deterioration being softness, bleeds, molds and internal breakdown; different interpretations on product specifications by suppliers; and customers inflexibly that cannot turn promotions on quickly enough (Terry et al., 2011).

More than 85% of the complaints from retailers are due to fruits breakdown and mold development. To avoid losses, it is essential to maintain strawberries as close as possible to their optimal temperature (0 °C) from harvest until consumption. However, sometimes in Summer and during promotions retailers have no refrigerated space or choose to display the fruit in non-refrigerated areas to increase sales. This practice can lead to higher losses not only in store but also in the costumer household. At retail stores the waste was estimated in the United Kingdom at 2 to 4%, mainly due to insufficient temperature control capacity in-store and back- of-store (and wholesale) especially for high promotion volumes (e.g. gondola ends) during the Summer; inappropriate stacking (side stacking) of clamshells; and inaccurate forecast of demand and demand fluctuations (Terry et al., 2011). Demand for strawberry in the United Kingdom can increase by 40% when the hot weather is installed (Terry et al., 2011).

A large percentage of the waste at retail level is avoidable. In many instances, a clamshell is discarded in the store if it contains one single damaged fruit; even though most fruit in the package are fit for consumption, the cost of repacking leads to the rejection of the whole selling unit (Terry et al., 2011).

The percentage of fruit wasted at the consumer household level can be large. In Europe, most of the total supply chain waste occurs in the field followed by the consumers households (Sonesson & Meybeck 2011). However, close to 15% of the wasted fresh fruits could be avoidable. The major cause of waste that occurs in the consumer house is due to excess storage time after purchase with 80% of the consumers admitting not consuming the purchased fruit in time (Murphy & Quested, 2014). In Portugal close to 10% of the fruits produced are wasted at consumer level (Batista et al., 2012).

Packaging

Strawberries are very sensitive to compression and vibration damage and very susceptible to water loss. Therefore, packaging must be chosen to provide physical protection to the fruits. Postharvest life can be increased by the package type and the packaging method (Jobling, 2000). Generally, strawberries are harvest to polyethylene terephthalate (PET) or recycled PET clamshells with a clip-on lid or a heat seal film. The bottom of the clamshell is usually

padded with a bubble wrap to minimize vibrational damages. These clamshells (primary packaging) are usually placed in returnable plastic trays (Terry et al., 2011).

One of the biggest consequence of the temperature fluctuation is the condensations inside the clamshells that increase the potential for fungal disease infection (Mirzaee & Bishop, 2010). The clamshells must be vented to allow air circulation through the fruits to minimize possible condensations (Linke & Geyer, 2013).

Quality of strawberry fruit

To properly address quality, it is important to distinguish objective quality from perceived quality. While objective quality may be described as “the measurable and verifiable superiority on some predetermined ideal standards”, perceived quality is linked to the consumer’s perception of the product. Consumer perceived quality depend on prior experience, purpose of use or quality consciousness (Hansen & Solgarrrd, 2004).

Characteristics of quality

Strawberry is a non-climacteric that does not ripe after harvest (Thompson, 2015). Ethylene production rate of strawberry is very low and remains relatively unchanged during ripening. Exposure to exogenous ethylene do not enhance ripening but can increase disease development and decay incidence (Mitcham et al., 1996).

It is essential to harvest the fruits at their optimal maturity, fully ripe, or with at least 3/4 of the fruit showing red color. For high quality the fruits must be uniformly red, firm, flavorful and free of defects and disease (Mitcham, 2014). For consumer acceptable flavor, the fruit should have a minimum of 7% soluble solids and not more than a 0.8% titratable acidity (Mitcham et al., 1996).

Appearance is a dominant aspect in the perception of freshness by the consumers; withered sepals, bruises, and decay are major appearance defects (Péneau et al., 2007). In addition, fruit shape and uniform size of the batch are key to the overall appearance of the selling unit.

Flavor, and the related taste and odor, are also essential quality characteristics. Fermentation odor, spongy texture, sour and fermentation flavor negatively affect quality perception (Péneau et al., 2007).

Weight loss

Weight loss in strawberries can lead to poor appearance due to development of shriveling, dryness of the calyx, and darkening red color (Nunes et al., 2005). Water is the main component of strawberries, accounting for 91% of its total weight (INSA, s.d.). Water loss can be rapid if the fruit is not stored at low and constant temperature (Nunes et al., 1998).

According to Nunes and Emond fruit stored at 20 °C in just 2 days lose twice as much weight (6% of their initial weight) than fruit stored at 0, 5, 10 and 15°C that may lose an average of 3% (Nunes, 2008). Weight loss can be minimized by packaging the fruits in clamshells immediately after harvest (Paraskevopoulou-Paroussi et al., 1995), however, closed packaging under variable temperatures can lead to condensations and consequently increase the incidence of fungal diseases (Berrie et al., 2002).

Weight loss on strawberries stored in fluctuating temperature was higher than in constant temperature (Nunes & Emond, 1999; Nunes et al., 2003; Mehrdad et al., 2008) increasing as temperature increased from 1 to 20°C (Nunes et al., 1998) According to Robinson et al. (1975) strawberries with more than 6% of weight loss become unmarketable.

Fruit and calyx color

Color is one of the most important quality attributes to consumers (Péneau et al., 2007; Crecente-Campo et al., 2012). Although red color may increase after harvest, in some cultivars, fruits harvested with less than 3/4 red color will not reach the same visual as those harvested at the proper maturity stage (Nunes et al., 2006).

Strawberry color is determined by anthocyanins. Pelargonidin-3-glucoside is the major strawberry anthocyanin, accounting for approximately 91.5% of the total anthocyanins, followed by cyanidin-3-glucoside; together these two anthocyanins account for 96% of the total (Crecente-Campo et al., 2012). Pelargonidin-3-glucoside is an unstable pigment and this can lead to a rapid fruit color loss (Cash & Sistrunk, 1970). Surface browning can develop during shelf-life due to anthocyanin degradation and oxidation of soluble phenolic compounds, possibly caused by an increase in polyphenol oxidase activity as a result of water loss (Nunes et al., 2005).

According to Collins and Perkins-Veazie (1993) after 15 days of storage, independent of the temperature, the Chroma and the hue angle of fruit decrease from 30 to 25 and 21° to 13°, respectively, indicating loss of brightness and color shift from orange-red to red.

The calyx color darkens over time regardless of storage temperature and browning may occur in the crown of the calyx at the point of pedicel attachment (Collins & Perkins-Veazie, 1993).

Firmness

Firmness is an important attribute to consumers when assessing fruit freshness (Péneau et al., 2007). Firmness of strawberry is not only important for their eating quality but also for their shipping ability. Soft fruit cannot be shipped over long distances without substantial losses due to physical injuries (Chandra et al., 2015).

Strawberries tend to soften when exposed to fluctuating temperatures during handling (Nunes & Emond, 1999) and when transferred from low to higher storage temperature (Luoto, 1984). Under a fluctuating temperature regime strawberry fruit become softer throughout most of the handling process indicating the advanced senescence of the fruit (Lai, 2010).

According to Nunes and Emond (1999) strawberry firmness decreases during storage, regardless of the temperature. Exposure to higher temperatures during storage may be the cause of greater softness (Collins and Perkins-Veazie, 2003). Fruit can become unacceptably soft after 2 days at 20 °C (Nunes, 2008). Firmness measured by deformation test decreases during shelf-life, at a higher rate at 21 °C than at 1 or 6 °C; the instrumental differences in firmness are perceived by a sensory panel (Lai, 2010). However, Shin et al. (2007) reported that the firmness of strawberries stored at 0.5, 10 and 20 °C increased over time, an observation that the authors attributed to an increase in pectin viscosity (the gelling behavior).

Soluble solids content (SSC)

The sugar content at harvest depends on the cultivar and growing conditions (Wang and Camp 2000). Strawberries harvested at early stages of color development have lower sugar content and the sugar levels do not change after harvest to make them suitable for fresh consumption (Kalt et al., 1993). Changes in the soluble solids content of strawberries during storage depends on temperature and initial ripeness (Nunes, 2008).

The postharvest evolution of SSC is not linearly related with temperature and depend on factors other than storage time and temperature. SSC of strawberries stored at 0, 5, and 10 °C were steady until day 5 but decreased drastically afterwards (Ayala-Zavala et al., 2004). Lai (2010) reported that soluble solids content of strawberries stored at different temperatures decreased regardless of the temperature and that the decrease in SSC was significantly faster in strawberries stored at 21 °C then in fruit stored at 1°C. However, according to Nunes et al. (2006), some strawberry varieties showed an increase SSC when stored for 8 days at 1°C leading to an increase of 9%.

Shin et al. (2007) reported an increase in strawberry SSC stored at 0 °C but measured reductions in SSC of fruits stored at 10 and 20 °C; this decrease reached 6.3% on the third day of storage.

Titrateable acidity (TA)

Several studies show that changes in strawberry acidity depend upon fruit maturity at harvest and storage temperature (Nunes, 2008). The TA of fruits harvested at three-quarters color decrease during storage at 1 °C reaching the same acidity as fruits harvested at the full-red stage (Nunes et al., 2006).

TA tends to decreased regardless on the storage temperature with fruits stored at 10, 15 and 21 °C showing a faster and higher reduction then those stored at 0 and 5 °C (Lai, 2010). However, Colling and Perkins-Veazie (1993) reported that total acidity of strawberries when stored at 1 and 5 °C did not changed significantly. These lack of changes in acidity during storage has also been observed by Cordenunsi et al. (2003) and Ayala-Zavala et al. (2004).

Decay development

Although physicochemical characteristics play a large role in the consumer acceptance and quality evaluation of strawberry, decay is a major concern for supply chain operators and the main cause of postharvest losses.

Botrytis and Rhizopus rot are the greatest cause of postharvest losses (Mitcham et al., 1996; Mitcham, 2014). While Rhizopus rot, caused by *Rhizopus stolonifer*, can be controlled by temperature since the fungus does not grow under 5 °C, *Botrytis cinerea* can grow even at 0 °C causing large postharvest losses (Mitcham et al., 1996). *Botrytis cinerea* can infect the fruit before harvest, remaining as a latent infection, inoculate wounds during harvest or colonize the fruit after harvest by contact with diseased fruit, a process called nesting (Nunes et al., 2012; Mitcham, 2014).

Botrytis cinerea can remain quiescent infection in immature strawberry fruits and only develop when the fruits become ripe (Jerch et al., 1989). Immature strawberries are more resistant to fungal attack than ripe ones (Jerch et al., 1989; Nunes et al., 2012); therefore, fruit harvested with a white tip show a lower rate of mold development regardless of the storage temperature. Disease incidence and severity increase with inoculation and higher storage temperature (Nunes et al., 2012).

Storage temperature has a strong effect on decay incidence and development. Takeda et al. (1990) reported more than 35% of affected fruits after 2 days storage at 18 °C. Decay development becomes faster and more severe as the temperature increases above 1 °C (Lai, 2010). Sommer et al. (1973) observed a high incidence of mold development in fruits stored without refrigeration, increased in wounded fruits, contrasting with fruits stored at 0 °C in which no lesion development was observed. Fruits stored at 10 and 20 °C showed an increasing decay incidence with higher relative humidity as storage temperature increased (Shin et al., 2007).

Prevention of mechanical injuries to the fruit is paramount to control postharvest decay. Wounded strawberries are more susceptible to fungal development that can later spread the disease to nearby healthy fruit. It is essential at harvest to avoid placing damaged fruits in the trays and during transport prevent vibration damages of the fruits (Mitcham et al., 1996).

Material and methods

Part I – Temperature throughout the supply chain logistic circuits

Part II – Temperature effects on strawberry quality and self-life

This thesis contains two experimental sections that will be described separately. Section I addresses the actual temperatures in the strawberry supply chain, from farm to the final selling point and household refrigerator. Experiments in section II were performed under controlled conditions to assess the effect constant temperature at different values on quality changes of strawberry fruit.

Part I – Temperature throughout the supply chain logistic circuits

Two logistic circuits were chosen to monitor fruit and air temperature from farm to retail outlet.

The experiments were conducted in 9th June 2016 in a load of strawberries harvested in a farm located in Santa Catarina, Caldas da Rainha and delivered to a retail store from a major distribution chain located in Amadora, and in 6th July 2016 in another load harvested at São Teotónio, Odemira, and delivered to the same retail store.

Operations performed upon the fruit on the supply chain were described and the period between operations and steps in supply chains were registered. Fruit, package and air temperature was monitored in two circuits.

Strawberry packaging

Primary, secondary, and logistical packaging and unitization were the predominant in the supply chain of the retailer.

Strawberry used in these experiments were packed into vented 500 g lidded PET clamshells, the dominant primary package for strawberry in the Portuguese modern distribution in 2016. Primary packages were placed inside reusable polypropylene trays (400 × 600 mm) containing 10 primary packages as shown in figure 4.

The secondary packages were palletized onto an 800 × 1200 mm wood pallet to a high of 18 trays (fig. 4).

Temperature measurement in the strawberry load

Temperature was measured with Tinytag talk 2 dataloggers (Gemini data loggers, Chichester, West Sussex, UK). Model TK-4014 without a probe was used to measure air temperature and model TK-4023 containing a fruit probe used to measure temperature inside the fruit. Gemini

Tinytag talk 2 dataloggers have a resolution of 0.05 °C and were programmed to register the temperatures at 30-second intervals throughout the whole supply chain from the grower to the consumer household.

In each commercial circuit analyzed, the temperature was measured on tree clamshells inside CHEP boxes of one expedition unit with the following distribution:

- One datalogger to measure the air temperature;
- One datalogger to measure the air temperature inside the clamshell;
- Two dataloggers to measure the temperature inside the fruits.

The clamshells with the dataloggers were located in the top, the middle and the bottom of the palette (fig. 4).

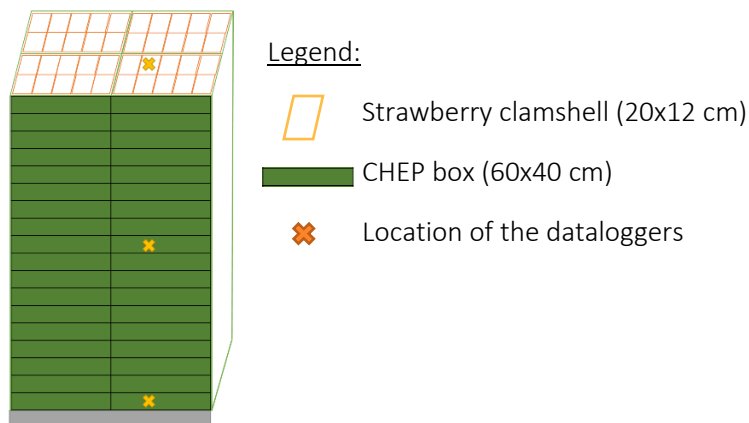


Figure 4 - Expedition unit with the location of the dataloggers.

The dataloggers were placed in the load at harvest and collected at the consumer household. The data were transferred from the datalogger to a computer using the Tinytag Explorer 4.9 software interface (Gemini, UK) and used for subsequent analyses.

The accumulated time-temperature (ATT) was calculated for each stage by multiplying the average temperature by the duration of the stage and adding all the partial results along the supply chain.

Temperature measurement in car trunks and domestic refrigerators

The air temperature was recorded in trunks of five private vehicles and five domestic refrigerators in Lisbon between June 30th and July 4th, 2016. The vehicles were all dark in color: (1) Toyota Yaris 2015; (2) Audi A4 2014; (3) Renault Megane Break 2007; (4) Citroen C5 Tourer 2009; (5) Skoda Octavia Break 2012.

The domestic refrigerators analyzed were: (1) Balay (with no further data); (2) AEG Electrolux C6 18 40 4i class: A +; (3) Bosch KGD36VI30 class: A ++; (4) AEG Electrolux Santo N81840-4i class: A; (5) Hoover HDCF 184 X / 1, class: A +.

The temperatures were measured continuously at intervals of 1 minute with registers Tinytag Talk 2, TK-4014 (Gemini data loggers, Chichester, West Sussex, UK). The dataloggers were placed inside the trunks with free movement and in the front of the bottom shelf, on the door opening side of the refrigerator.

Part II – Temperature effects on strawberry quality and self-life

Fruit material and storage conditions

Strawberry (*Fragaria × ananassa* 'Portolas') fruit were harvested in April at the full red color stage. The fruit were packed into 500 g vented clamshells, forced air-cooled to 7.5 °C and transported to the laboratory in refrigerated temperature.

Each clamshell was weight and then placed in walk-in rooms set at five different storage temperatures: 0, 5, 10, 15, and 20°C. Actual storage air temperature and relative humidity, were monitored throughout the trials and found to be 1 ± 1 °C, 90 ± 2 %; 5 ± 2 °C, 90 ± 2 %; 10 ± 1 °C, 85 ± 5 %; 14 ± 1 °C, 90 ± 3 %; 20 ± 2 °C, 90 ± 3 % for 0, 5, 10, 15 and 20 °C, respectively.

The experiment was repeated in July 2016 with 'Candongra' strawberry handled as described.

Sampling schedule

Before the beginning of the temperature trials (day 0) five clamshells of strawberries were analyzed to characterize the initial conditions of the fruit. Five clamshells of strawberries per temperature treatment were analyzed on days 3, 5, 7, 10, 12 and 14 for 0, 5 and 10°C and on days 3, 5 and 7 for 15 and 20°C (table 2).

Table 2 - Map of samples testing days.

Day	0°C	5°C	10°C	15°C	20°C
0			X		
3	X	X	X	X	X
5	X	X	X	X	X
7	X	X	X	X	X
10	X	X	X		
12	X	X	X		
14	X	X	X		

Fruit analyses during shelf-life

Strawberry quality was accessed during shelf-life under each storage conditions based on the following dependent variables: Weight loss; fruit surface color; calyx color; firmness; soluble solid content, and titratable acidity.

Analyses were performed 5 fruit in each of 5 clamshells until the development of rot or mold rendered the unit unsuitable for the experiment, at which time it was discarded.

Weight loss

Individual clamshells were weighted in an accuracy balance (Kern PFB 2000 - 2, Kern & Sohn GmbH, Germany) with 0.01 g precision. replicated measurements were made at each sampling time. The weight loss was calculated using Equation 1 and expressed as percentage of the initial fresh weight.

$$\text{Weight loss} = \frac{W_i - W_t}{W_i} \times 100 \quad [\text{Eq. 1}]$$

where W_i is initial weight and W_t weight at the testing day.

Fruit surface and calyx color

Five representative strawberries were selected from each clamshell and the calyx carefully separated from fruit. Fruit surface color was measured in the middle of equatorial region and the calyx color on the top of the sepals.

Color was measured in the CIELab color space (L^* , a^* , b^*) with a tristimulus colorimeter (Chroma Meter CR-400, Konica Minolta, Japan) using the C illuminant and observer at 2 °.

The colorimeter was calibrated with a ceramic white ($L^*=97.10$; $a^*=0.19$; $b^*=1.95$) before each set of measurements.

Lightness, Chroma and hue angle are reported. Chroma and hue angle were calculated from the a^* and b^* values using equations 2 and 3, respectively. The lightness (L^*) gives the variation between black ($L^*=0$) and white ($L^*=100$). Chroma (C^*) gives the color saturation and the hue angle (H°) with 0° , 90° , 180° and 270° being red-purple, yellow, bluish-green and blue respectively (Nunes et al., 1995).

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad [\text{Eq. 2}]$$

$$H^\circ = \tan^{-1} b^* / a^* \quad [\text{Eq. 3}]$$

Firmness

Fruit firmness was measured in the 5 strawberries from each of 5 clamshells with TA.XT2 plus texture analyzer (Stable Micro Systems, Surrey, UK), using a 2 mm diameter plunger to perform a penetration test into 5 mm depth of the fruit, at a speed of 1.7 mm/s (Doving and Mage 2002). The test was performed in the equatorial region of each fruit.

Soluble Solid Content and Titratable Acidity

Strawberries were homogenized into a puree with a hand blender and then filtered through gauze. Soluble solid content was measured with a digital refractometer (HI 96801, Hanna Instruments, Woonsocket, RI, USA).

Strawberry juice (6 g) was diluted in 100 mL of distilled water. The diluted juice was titrated with a 0.1 M NaOH to pH 8.1 and TA expressed as percentage of citric acid equivalents (Nunes et al., 1995).

Sensorial analysis

A panel of 10 people, with 6 women and 4 men, being 5 under and 5 above 30-year-old, scored the fruit for odor, texture, juiciness, flavor and overall liking. Each panelist was served 2 representative fruit (whole) previously placed at room temperature and asked to score for the different attributes in a 1 to 5 scale. The tasting sheet and the grades applied to each parameter are in annex I.

Damage typology and severity

Preliminary screenings for damage types were performed in strawberry samples to determine the predominant damages and define the scale to score their severity. The following types of damage were considered relevant to evaluate strawberry losses: mechanical bruises, rots and molds. Damage typology cards were developed based on these preliminary observations.

The strawberries were separated in 5 classes. The classification of each fruit was made according to the flow chart of figure 5.

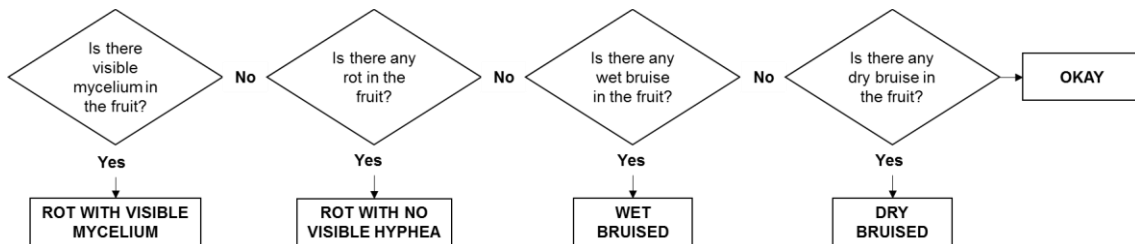


Figure 5 - Flow chart to classification of damages.

Dry bruised (fig. 6) are characterized by regions that can be depressed on the fruit and a dried appearance with a whitish to yellowish color.



Figure 6 - Strawberries with dry bruises.

Wet bruised (fig. 7) are fruits with areas that usually present cell disintegration and consequently wet appearance.



Figure 7 - Strawberries with wet bruises.

Rot without visible hyphae (fig. 8) are characterized by fruits with necrotic and usually softened areas showing a brownish color.



Figure 8 - Strawberries with rot without visible hyphae.

Rot with visible mycelium (fig. 9) characterized by the mycelium development becoming visible in an area or the entire fruit.

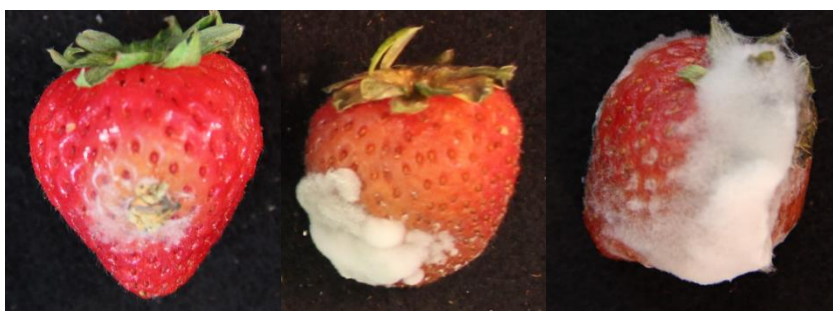


Figure 9 - Strawberries with rot with visible mycelium.

The number of strawberries in each class was registered and the results expressed as percentage of the total fruit number.

Results and discussion

Part I - Temperature throughout the strawberry supply chain

Part II – Temperature effects on strawberry quality and self-life

Part III – Estimation of quality depreciation in the strawberry supply chain

Part I - Temperature throughout the strawberry supply chain

Temperature was monitored in two circuits. We start by describing the circuit stages and operations, and then present the temperatures measured inside the fruit, into the clamshell and in the air outside the packages at different locations of the pallet.

Commercial circuit 1

Description of the circuit

Circuit 1 started with fruit harvest in a farm located in Caldas da Rainha on April 2016, and ended at a household in Oeiras after 157 hours (6 days and 13 hours).

The circuit involved the operations and operators indicated in tables 3 and 4.

Table 3 - Summary description and responsible operator of each operation.

Operation	Description	Operator
Harvest	Fruits were harvested directly into 500 g clamshells and then placed 10 units in white plastic boxes that were temporary placed in the field on a pallet.	Farmer / producer
Transport to packing house	When several boxes were placed a tractor transported the pallet to the packing house (refrigerated).	Farmer / producer
Palletization	The white field boxes with the clamshells inside were stacked until the forced air chamber was full.	Farmer / producer
Forced air cooling	The fruits were then cooled down with the predefined cycle.	Farmer / producer
Repacking	After cooled down each clamshell was weighted, labelled and placed in the CHEP expedition box.	Farmer / producer
Temporary storage	Until expedition fruits were placed in a cooling chamber at 0 °C.	Farmer / producer
Transport to warehouse	Transport was made by the producer in a refrigerated truck.	Farmer / producer
Warehouse temporary storage	After unloaded the pallets were maintained in a refrigerated place.	Retailer

Table 4 - (continued) Summary description and responsible operator of each operation.

Operation	Description	Operator
Store palletization	The pallet containing the strawberries were re-palletized according to the order from the store.	Retailer
Transport to store	Transport was done by the retailer in a refrigerated truck.	Retailer
Arrival to the store	When arrived to the store the boxes were placed in a refrigerated hall.	Retailer
Store display	The fruits were then placed in the store inside the CHEP boxes in the fruit non-refrigerated area.	Retailer
Purchase by costumer	The fruits were purchased by a consumer and taken inside the CHEP boxes.	Costumer
Transport in the trunk	The boxes with the clamshells were placed in the consumer trunk and transported into his house.	Costumer
Storage in domestic refrigerator	At consumer house the clamshells were placed into the domestic refrigerator.	Costumer

The circuit contained 15 steps involving 3 different operators and 3 transportation linkages between them.

The times and distances from each stage are represented in Figure 10.

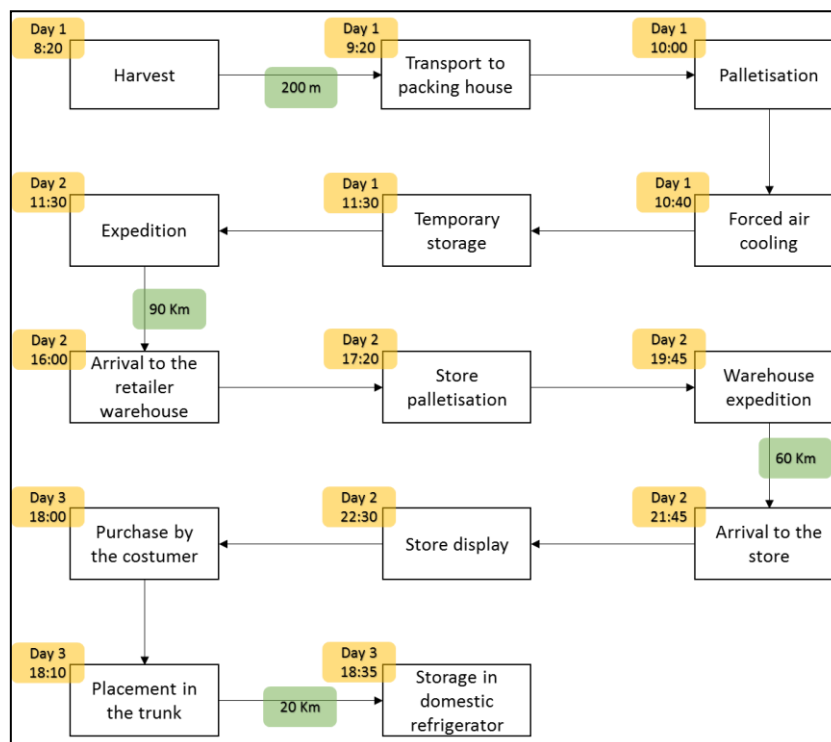


Figure 10- Strawberry supply chain from circuit 1.

This circuit took 2 days from harvest until the fruit were purchased. The fruits travelled a total of 170 km, during which there is opportunity for vibrational damages.

Temperatures in the circuit

Figure 11 presents the temperatures registered from harvest until household storage in a refrigerator.

Immediately after harvest fruits had an internal temperature of about 22 °C, with ambient temperature being 25 °C. The maximum air temperature was 38.4 °C measured at 9:20, immediately prior to transport to the packinghouse corresponding to 30.3 °C inside the fruit. At 11:20 (end of the forced air-cooling program), the average temperatures were 5 °C inside the clamshell, although the interior of the fruit never reached temperatures below 10 °C.

After the fruit were placed in the cold room, five and a half hours were required for the flesh temperature to decrease from 10 °C to 1.5 °C; after 17:00 the internal temperature ranged between 1 and 1.5 °C.

The temperatures did not differ among fruits placed on the same box. However, differences higher than 5 °C were registered at different positions of the pallet (fig. 12) at the at same stage of the supply chain.

From the expedition from the producer until the arrival at the store temperatures were 4 °C higher at the top of the palette when compared to the other two locations (fig. 12), however inside the fruit the differences were lower, with an average difference of 2 °C (fig.13).

While in the warehouse the top of the palette reached an air temperature of 9.9 °C with the fruit reaching 9.2 °C and remaining above 7.2 °C during the whole stage. In the other pallet locations the temperature reached 9.6 °C.

During transportation from the warehouse to the store the average temperature was 7.7 °C in the middle of the pallet. In store the maximum air temperature in the clamshells was 17.5 °C at 17:55, with 19.1 °C inside the fruit. Instead of a high increasing rate of the temperature when placed on the store, a trend of temperature increase was observed from the display in the store until the acquisition by a consumer.

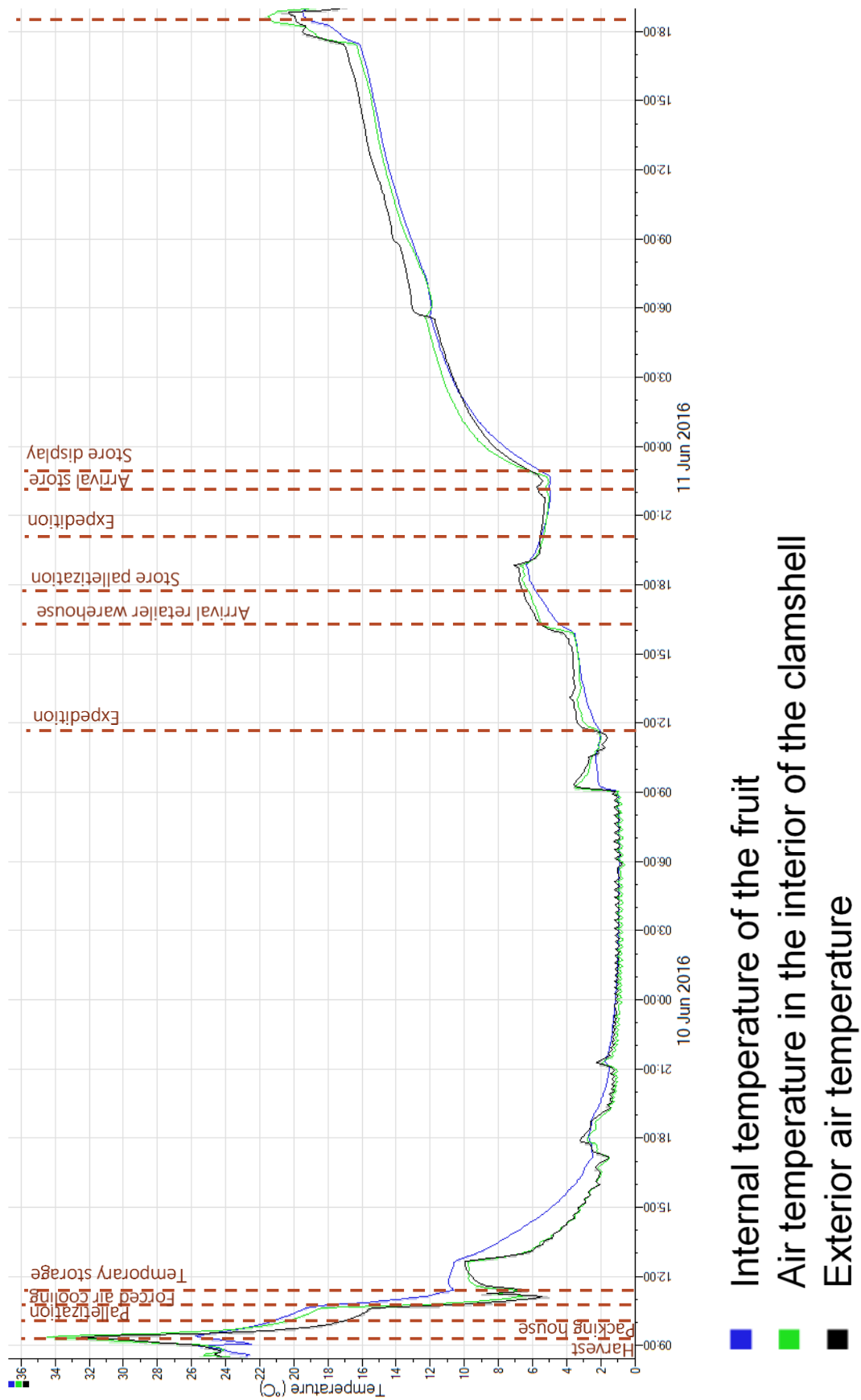
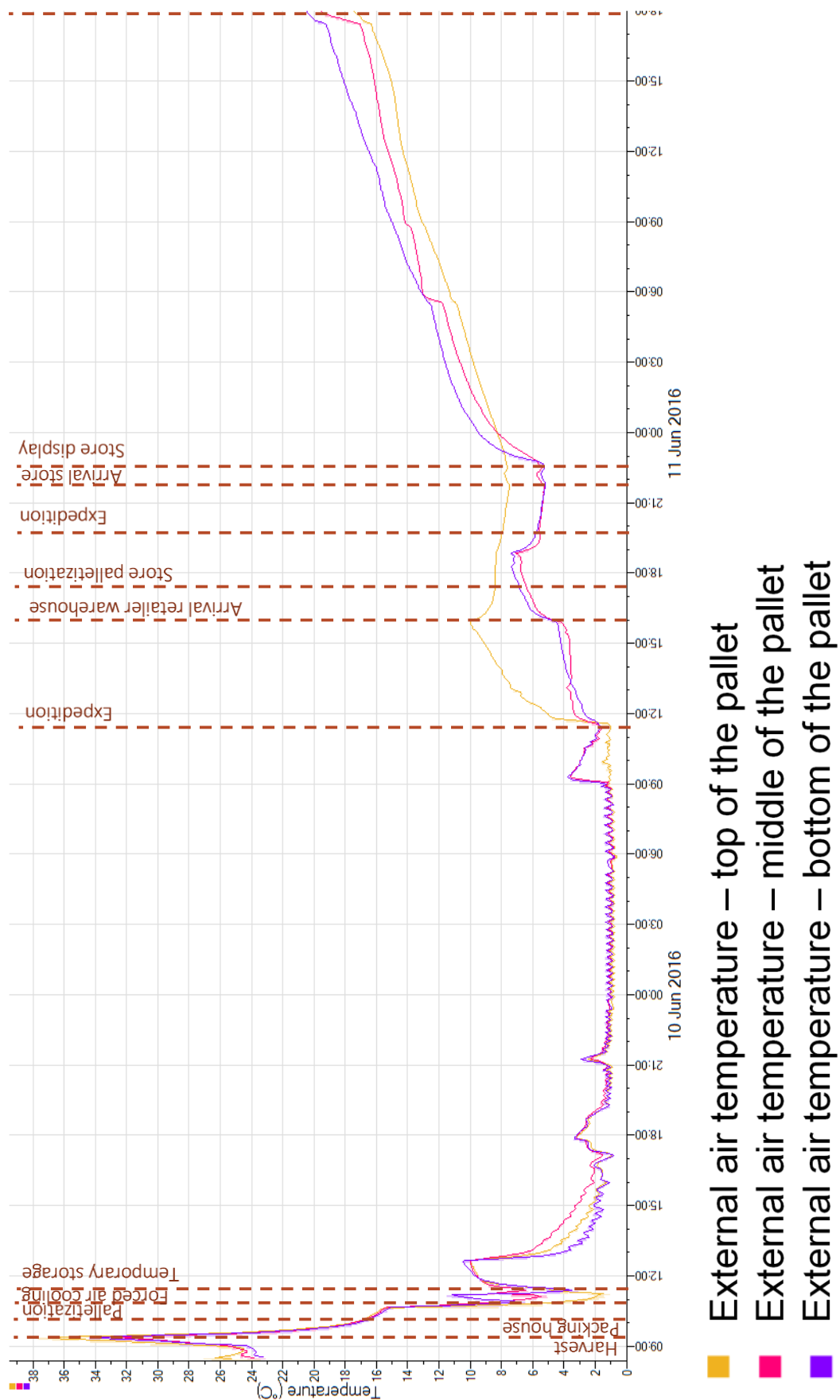
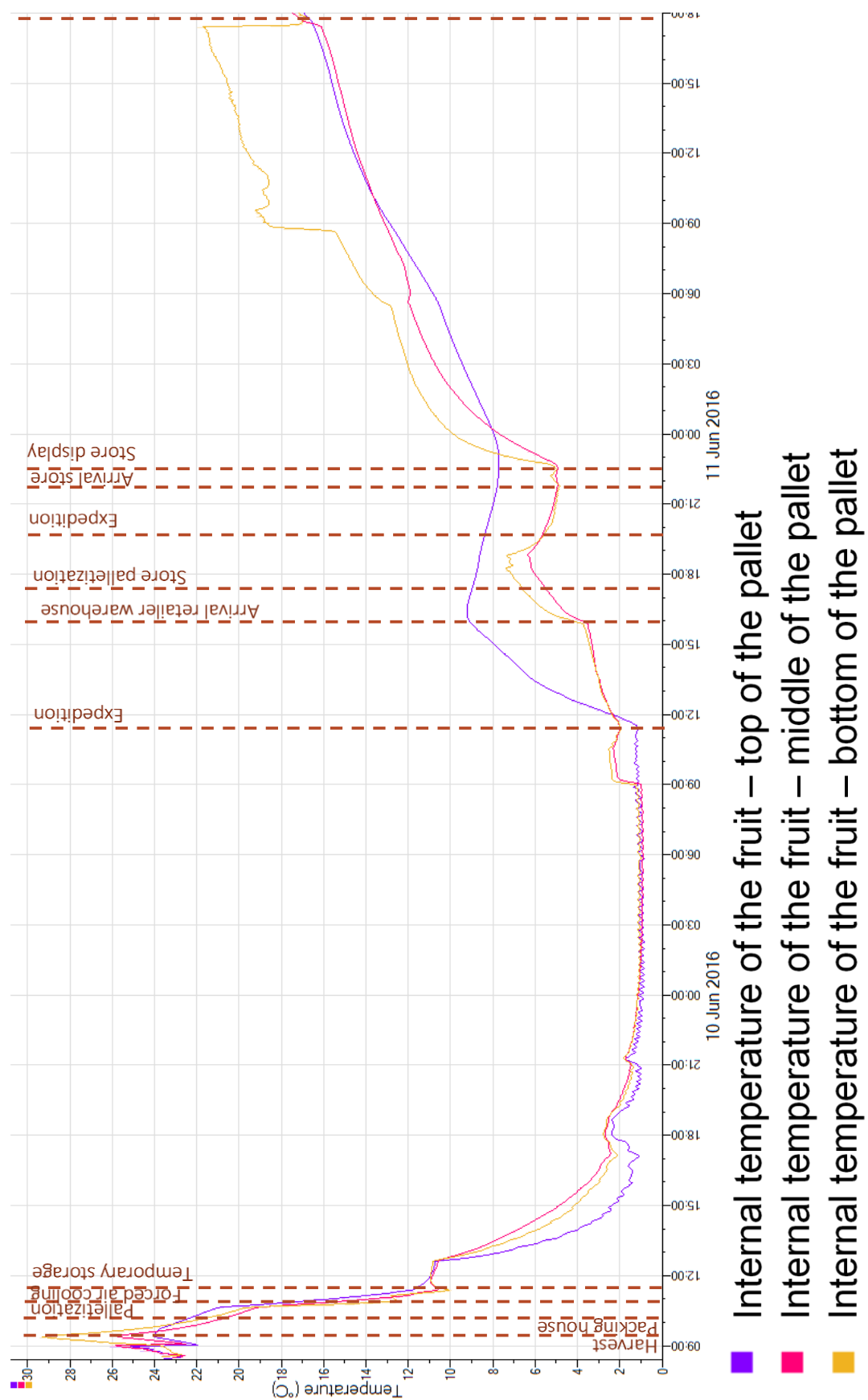


Figure 11 - Temperatures at different places of the clamshell from harvest until storage in consumer refrigerator.





Duration of exposure at different temperatures

Temperature affects the rate of depreciation of strawberry fruit (Shin et al. 2007). Therefore, strawberry quality in the supply chain depends on both temperature and duration of exposure in each step. Tables 5 and 6 presents the overall time-temperature exposure of the strawberries in circuit 1.

Table 5 - Exterior air temperature range, mid-point, duration, time-temperature (TT) and ATT of each supply chain step recorded on the middle of the pallet from the circuit 1.

Step	Temperature range (°C)	Mid-point temperature (°C)	Duration (h)	Time x temperature (°C h)	Accumulated time-temperature (°C h)
Harvest	24.5 – 37.7	29.4	1.0	29.4	29.4
Transport to packing house	17.3 – 37.7	25.7	0.7	17.1	46.5
Palletization	11.3 – 17.3	16.1	0.7	10.7	57.3
Forced air cooling	11.3 – 1.3	4.2	0.5	2.1	59.4
Repacking	1.3 – 8.9	5.8	0.5	2.9	62.3
Temporary storage	0.6 – 10.1	2.2	24.0	52.8	115.1
Transport to warehouse	1.1 – 10.0	7.8	6.5	50.7	165.8
Warehouse temporary storage	8.4 – 9.6	8.7	1.3	11.6	177.4
Store palletization	7.9 – 8.4	8.3	2.4	20.1	197.4
Transport to store	7.5 - 7.9	7.7	2.0	15.4	212.8

Table 6 - (continued) Exterior air temperature range, mid-point, duration, time-temperature (TT) and ATT of each supply chain step recorded on the middle of the pallet from the circuit 1.

Step	Temperature range (°C)	Mid-point temperature (°C)	Duration (h)	Time x temperature (°C h)	Accumulated time-temperature (°C h)
Arrival to the store	7.5 – 7.8	7.7	0.8	5.8	218.6
Store display	7.6 – 17.5	12.7	21.5	273.1	491.7
Purchase by consumer	17.5 – 17.6	17.5	0.2	2.9	494.6
Transport in the trunk	17.5 – 19.4	18.6	0.4	7.8	502.3
Storage in household refrigerator	19.4 (When placed)	-	-	-	-

In this supply chain an accumulated time-temperature (ATT) of 502.3 °C h was reached. If in this same circuit the temperature was kept at the optimal level for strawberry (0 °C) the ATT would have been 62.4 °C h instead of the 502.3 °C h registered, which represents an 8-fold reduction.

The largest contribution to the accumulated temperature was from the store display. Yet the temperature registered in the store can get much higher, with the temperatures in the store reaching close to 25 °C (Nunes et al., 2009), in the non-refrigerated area, which would result in a total of 537.5 °C h instead of the 273.1 °C h registered in this circuit during store display. However, if the fruit were stored at the average temperature found in strawberry refrigerated display, 5.7 °C (Nunes et al., 2009) the accumulated temperature could be reduced to 122.6 °C h or even 21.5 °C h if stored at their optimal temperature 0 °C.

The fruits were exposed to high temperatures (37.7 °C) at harvest, which account for significant part of the total ATT (6%) even though the time of exposure seems relatively short.

Commercial circuit 2

Description of the circuit

Circuit 2 started with fruit harvest in a farm located in São Teotônio on July 2016, and terminated at a household in Santiago do Cacém after 118 hours (4 days and 22 hours).

The circuit involved the operations and operators indicated in table 7 and 8.

Table 7 - Summary description and responsible operator of each operation.

Operation	Description	Operator
Harvest	Fruits were harvested directly into 500 g clamshells and placed in the field on a pallet.	Farmer / producer
Transport to packing house	When several boxes were placed a tractor transported the pallet to the packing house (refrigerated).	Farmer / producer
Palletization	The boxes with the clamshells inside were stacked until the forced air chamber was full.	Farmer / producer
Forced air cooling	The fruits were then cooled down with the predefined cycle.	Farmer / producer
Temporary storage	Until expedition fruits were placed in a cooling chamber at 0 °C.	Farmer / producer
Transport to transporter warehouse	Fruits were transported to an intermediate temporary storage.	Transport company
Transporter warehouse temporary storage	Fruits were maintained at approximately 5 °C.	Transport company
Transport to retailer warehouse	Transport was made by the transport company in a refrigerated truck.	Transport company
Warehouse temporary storage	After unloaded the pallets were maintained in a refrigerated place.	Retailer
Store palletization	The pallet containing the strawberries were re-palletized according to the order from the store.	Retailer
Transport to store	Transport was done by the retailer in a refrigerated truck.	Retailer
Arrival to the store	When arrived to the store the boxes were placed in a refrigerated hall.	Retailer

Table 8 - (continued) Summary description and responsible operator of each operation.

Operation	Description	Operator
Store display	The fruits were then placed in the store inside the CHEP boxes in a non-refrigerated area.	Retailer
Purchase by costumer	The fruits were purchased by a consumer inside the CHEP boxes.	Costumer
Transport in the trunk	The boxes with the clamshells were placed in the consumer trunk and transported into his house.	Costumer
Storage in domestic refrigerator	At consumer house the clamshells were placed into the domestic refrigerator.	Costumer

The circuit contained 16 steps involving 4 different operators and 4 transportation linkages between them.

Temperatures in the circuit

The times and distances from each stage are represented in Figure 14.

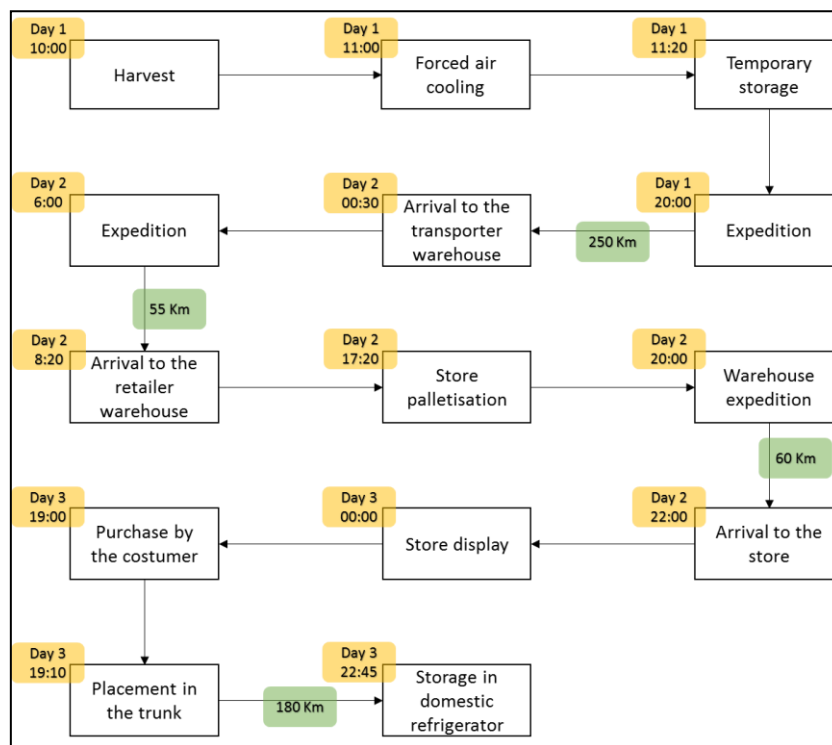


Figure 14 - Strawberry supply chain from circuit 2.

Fruit in this circuit took 3 days to arrive at the store. It involved a transporter company between the producer and a logistic warehouse, the fruits were stored for 5 hours in the transporter warehouse. The fruits travelled a total of 545 km from the place of harvest until the consumer house.

The fruits when arrived to the destination already presented a high percentage of visible bruises and in the following day started to collapse and juice running-off the clamshells. This can be result of the temperature breaks in the cold chain.

Temperatures in the circuit

The dataloggers were placed in the clamshells only at 15:00 (fig. 15) after the air-forced cooling, at that time the temperature inside the fruit was approximately 9 °C.

At 15:20 the temperature raised to almost 19 °C, however this increase in the temperature did not affected significantly the temperature inside the fruit (fig.16), which only increased 2 °C to 11 °C. Then the temperature decreased to approximately 5 °C and remained constant until preparation for shipping.

At 20:00, when shipped, a new peak of approximately 14 °C was observed, which did not affected the temperature inside the clamshell or the fruit that continued between 10-11 °C. During transportation, temperatures ranged between 5 and 6 °C and arrived to TIF (transporter subcontracted) with 11 °C which did not affect the internal temperature of the fruit.

While in the TIF, temperature variations from 4 to 13 °C were recorded. However, from TIF until the arrival at the store the fruit has always been exposed to a temperature below 8 °C with an average air temperature of 6.5 °C to 7.2 °C inside the fruit (fig. 16).

During the display in store a maximum temperature of 19 °C was reached at 19:00 coinciding with the time of purchase. The largest variations in fruit temperature were registered at the top of the pallet (fig. 16).

Based on the exterior air temperature registered on the top of the pallet it is possible to analyze all the breaks that occurred in the supply chain. Repalletization at the retailer warehouse shifted the box that were initially on the base to the top of the pallet.

When displayed in store the raise of the temperature was not immediate, indicating some obstacle to air movement (possibly a box placed on the top of the other). The temperatures of the fruit that transported on the top of the pallet at some stages differed almost in 10 °C when compared to the ones on the middle and bottom of the pallet (fig. 17).

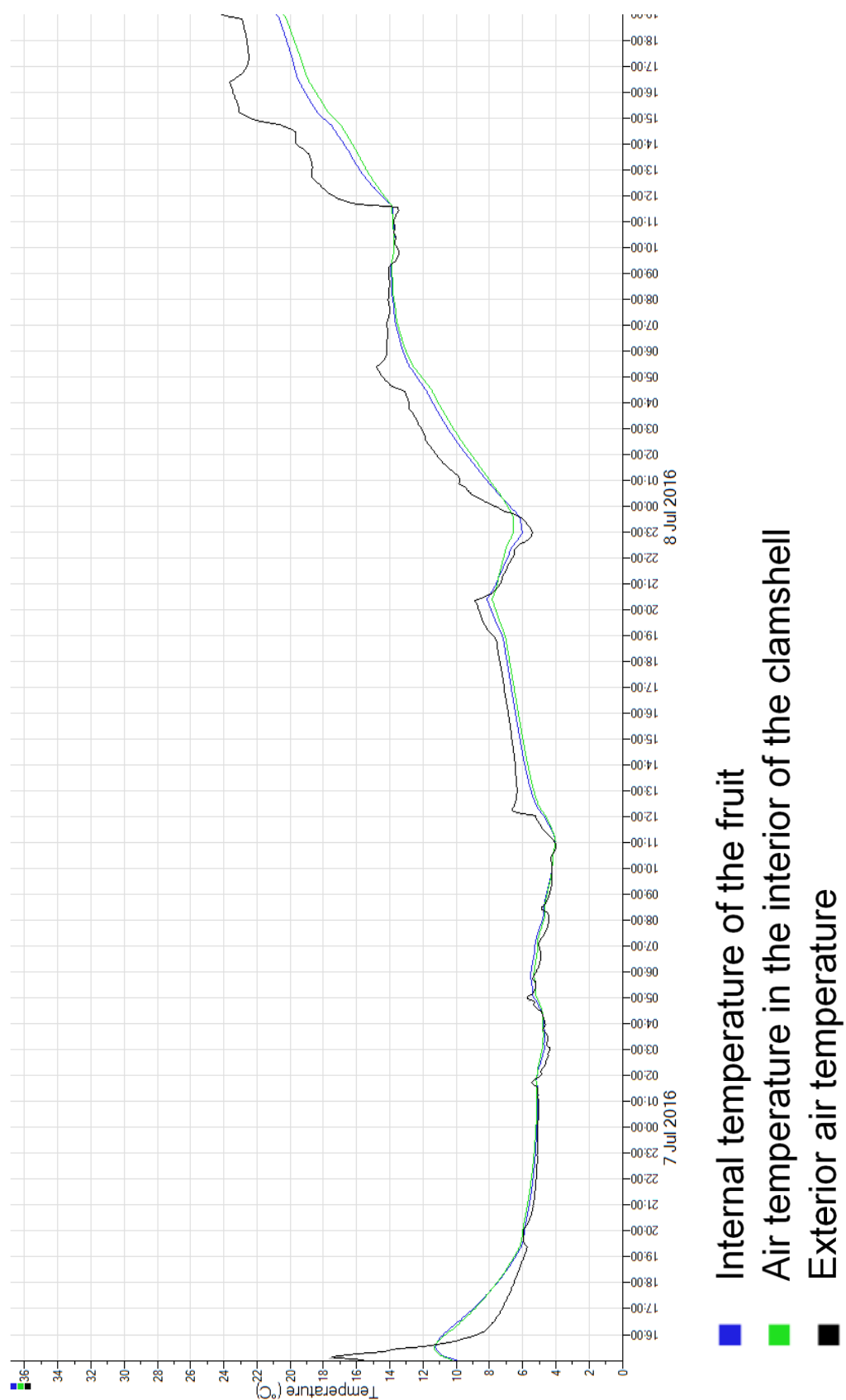


Figure 15 - Temperatures at different places of the clamshell from harvest until storage in consumer refrigerator.

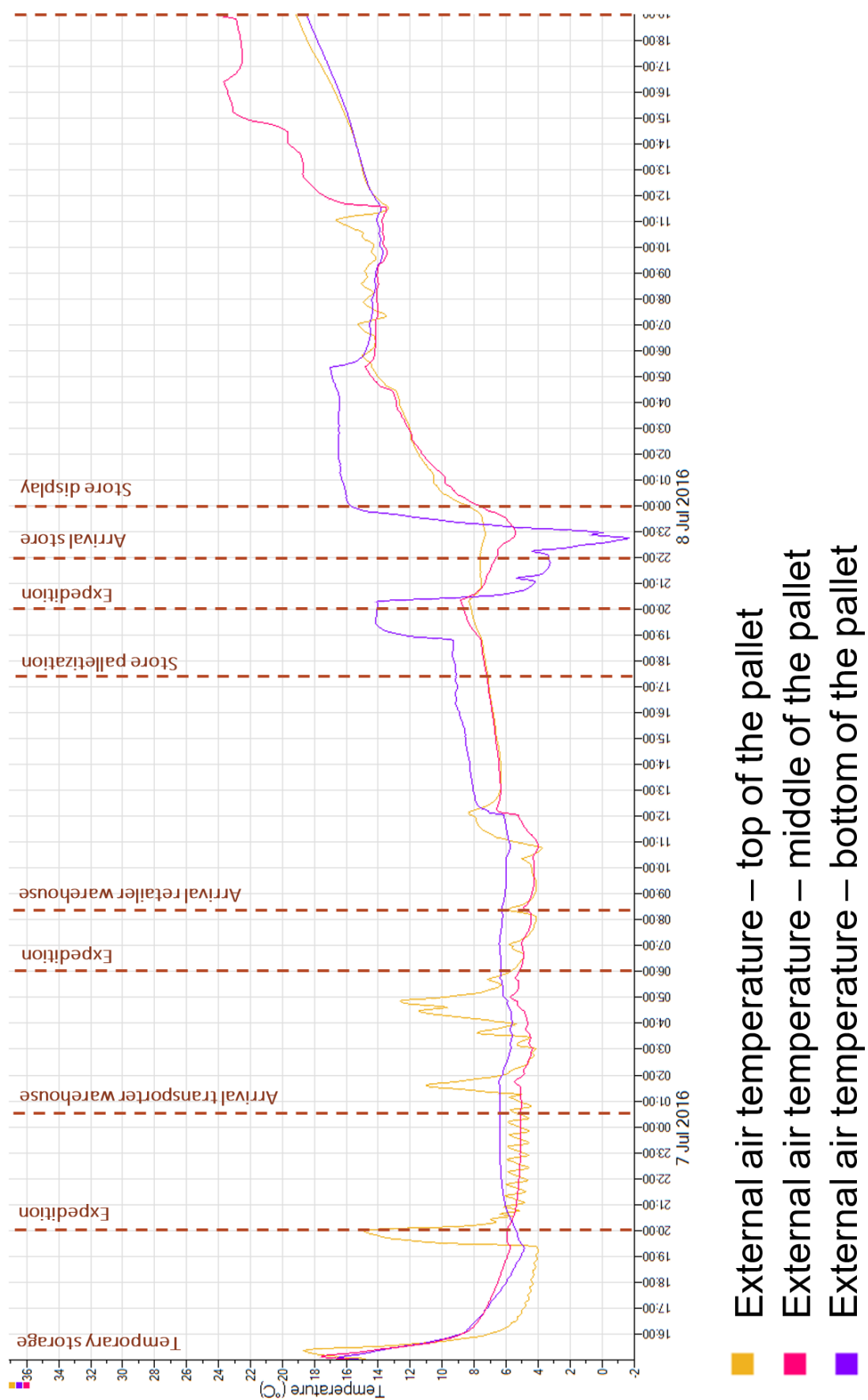


Figure 16 - External air temperature measured from harvest until storage in consumer refrigerator at different places of the pallet.

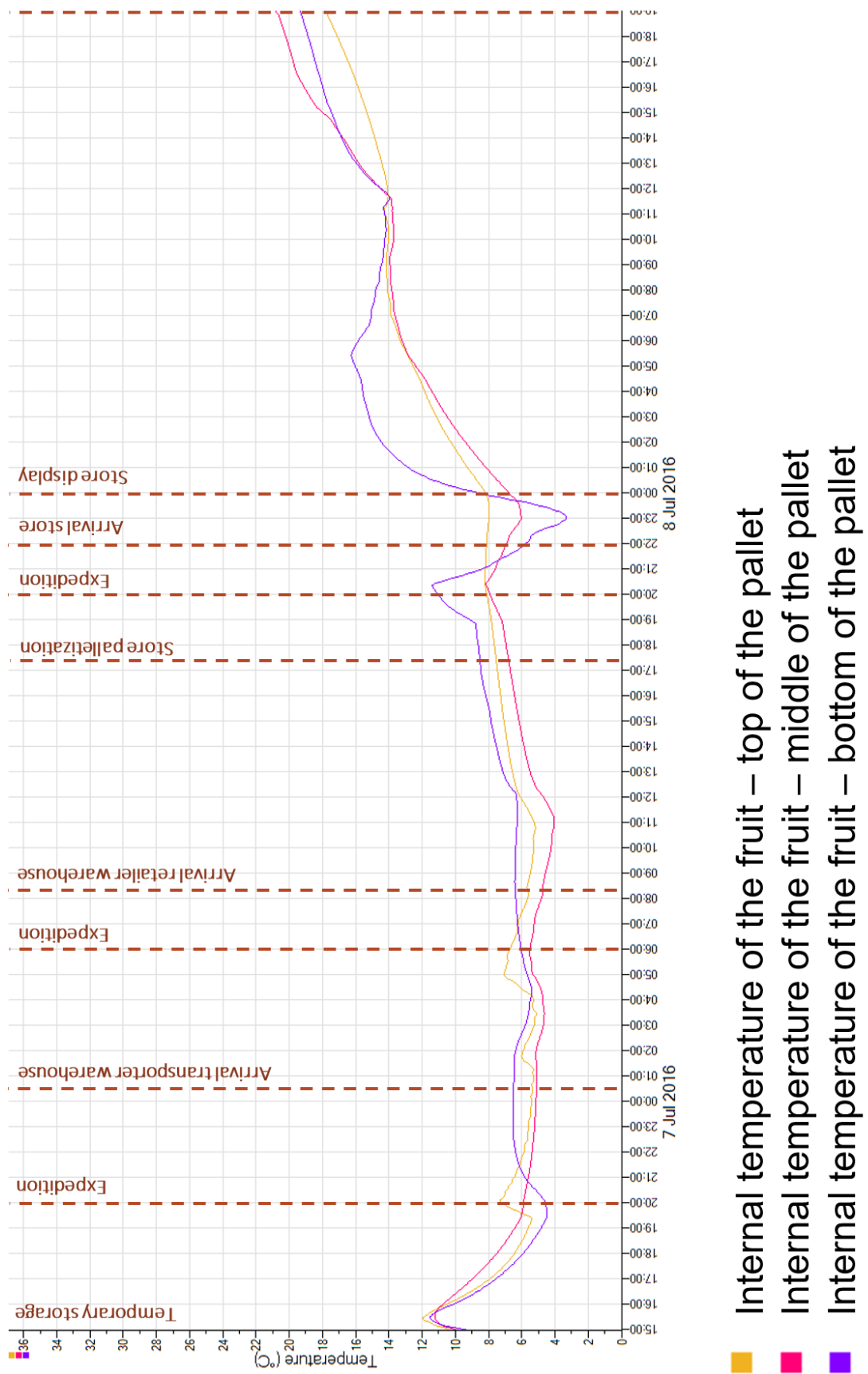


Figure 17 - Internal temperatures of the fruit from harvest until storage in consumer refrigerator at different places of the pallet.

In this circuit several major cold chain interruptions were observed, most noticed at the top of the pallet although the differences in temperature were not so evident in the fruits stored in other locations of the pallet.

Duration of exposure to different temperatures

Table 9 and 10 presents the overall time-temperature exposure of the strawberries in circuit 2.

Table 9 - Exterior air temperature range, mid-point, duration, time-temperature (TT) and accumulated TT of each supply chain step recorded on the middle of the pallet from the circuit 2.

Step	Temperature range (°C)	Mid-point temperature (°C)	Duration (h)	Time x temperature (°C h)	Accumulated time-temperature (°C h)
Harvest	-	-	0.5	-	
Transport to packing house	-	-	0.2	-	
Palletization	-	-	0.3	-	
Forced air cooling	-	-	0.3	-	
Temporary storage	4.0 – 18.7	8.7	5.0	43.5	43.5
Transport to transporter warehouse	4.5 – 14.3	5.8	4.5	26.1	69.6
Transporter warehouse temporary storage	4.1 – 12.7	7.2	5.5	39.6	109.2
Transport to retailer warehouse	4.1 – 5.8	4.9	2.3	11.4	120.6
Warehouse temporary storage	3.7 – 8.4	6.2	9.0	55.8	176.4
Store palletization	7.1 – 8.2	7.6	2.7	20.3	196.7

Table 10 –(continued) Exterior air temperature range, mid-point, duration, time-temperature (TT) and accumulated TT of each supply chain step recorded on the middle of the pallet from the circuit 2.

Step	Temperature range (°C)	Mid-point temperature (°C)	Duration (h)	Time temperature x (°C h)	Accumulated time-temperature (°C h)
Transport to store	7.5 – 8.3	7.8	2.0	15.6	212.3
Arrival to the store	7.3 – 8.4	7.5	2.0	15.0	227.3
Store display	8.5 – 19.2	14.8	19.0	281.2	508.5
Purchase by costumer	19.2 -19.5	19.4	0.2	3.2	511.7
Transport in the trunk	19.5 – 22.2	21.5	3.6	77.0	588.8
Storage in domestic refrigerator	22.1 (When placed)	-	-	-	-

In this supply chain, the temperatures were only registered 5 hours after harvest. From this time until storage in the consumer refrigerator, an ATT of 588.8 °C h was reached. As in circuit 1 the display in the store accounted for most of the ATT, with 281.2 °C h due to the fact that the fruit were not displayed in a refrigerated location.

However, if the fruit were stored at 5.7 °C (Nunes et al., 2009) in the refrigerated display the accumulated temperature would be 122.6 °C h or even 21.5 °C h if stored at their optimal temperature 0 °C just on this stage. An average temperature of 9.7 °C was registered since the thermometers were placed until fruit purchase. However, if the ideal storage temperature of 0 °C was maintained, the ATT could be of 111.4 °C h, which represents a reduction larger than 5-fold compared with that recorded in this circuit. Still, it would represent almost twice what could have been achieved in the first circuit.

'Last mile'

Consumer

The temperatures registered at different places of the clamshell during the storage in domestic refrigerators of circuit 1 and 2 are represented in figure 18 and 19, respectively.

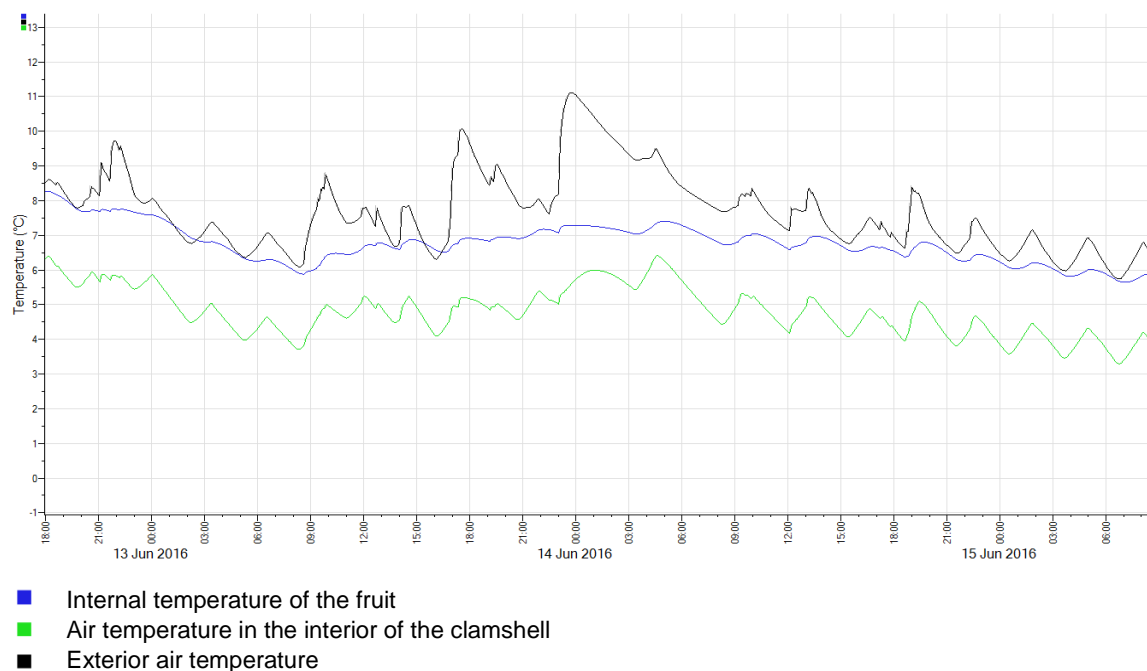


Figure 18 - Temperature measured from purchase at different places of the clamshell in the 1st circuit.

During storage in domestic refrigerator the temperature measured inside the clamshell was on average lower in 3 °C than the air temperature of the refrigerator. The changes of temperature that occurred due to the refrigerator cycles and the opening of the door also affected the temperature inside the clamshell but inside the fruit the difference was minimal. The average temperatures were 6.8, 7.7 and 4.8 °C inside the fruit, inside the refrigerator and inside the clamshell, respectively.

The temperature at which the fruits were stored (2 days and 15 hours) led to an accumulation of the temperature of 669.9 °C h. This is more than accumulation that occurred from harvest until purchase in this same circuit, being the storage temperature in the consumer household essential to the maintenance of the fruit quality.

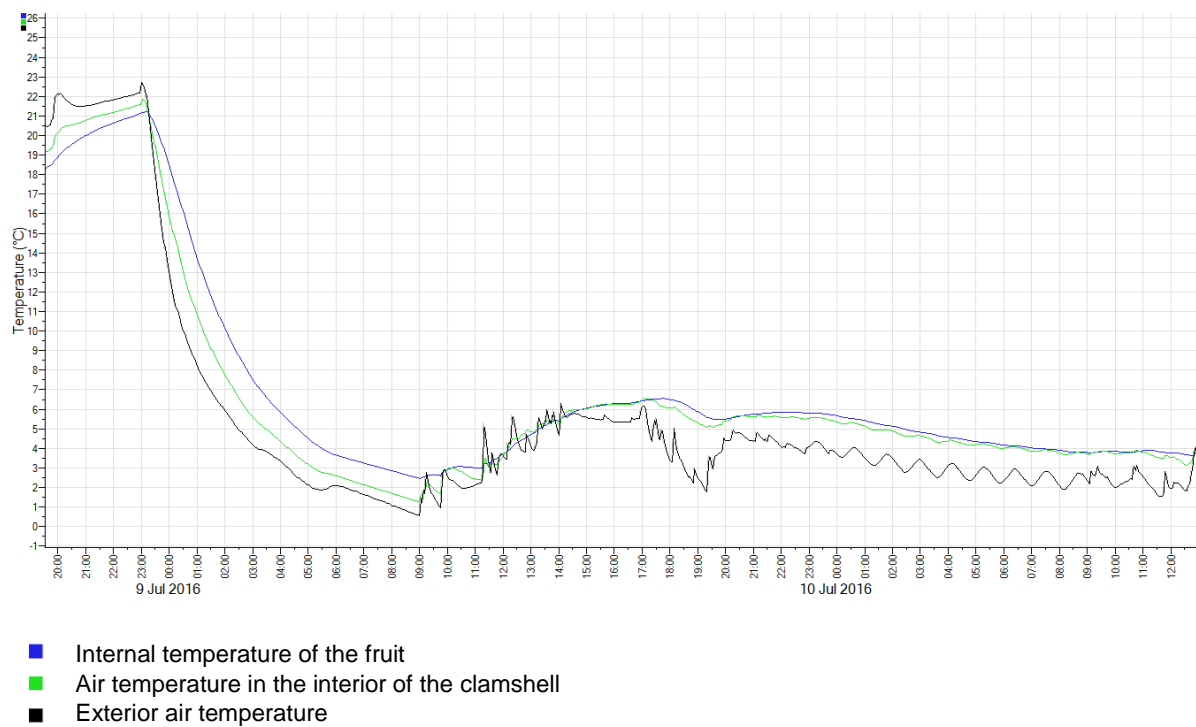


Figure 19 - Temperature measured from purchase at different places of the clamshell in the 2nd circuit.

On the 2nd circuit the fruits were transported in the trunk of the consumer vehicle for 180 km and then stored in a domestic refrigerator. The refrigerator was turned on only when the fruit were loaded inside. The initial temperature of the refrigerator was 22.2 °C and started to decrease 3 hours after switching on. It took 9 hours, since the fruits were placed in the refrigerator, for the temperature to decrease until 0.5°C, with the interior of the fruit recording 2.5°C.

During this period the temperature decreased at a similar rate in the refrigerator, inside the clamshell and inside the fruit, yet the temperature of the refrigerator was always lower, affecting then the temperature inside the clamshell and only later the inside of the fruit. It took more 45 minutes for the temperature inside the clamshell to reach the 10 °C mark and then more 45 minutes for the fruit to reach this same temperature. During this period were recorded average temperatures of 7.4, 8.8 and 10.5 °C on the refrigerator, the interior of the clamshell and the interior of the fruit, respectively.

After the refrigerator reached the 0.5 °C mark the fruits were stored an additional 28 hours period, with the fruits started to show a lot of bruising and rotting with runoff of juice occurring in some clamshells. During this stage the fruits registered an average internal temperature of 4.9 °C.

The temperatures recorded inside the refrigerator showed drastic changes in the temperature, with this ranging between 0.6 and 6.3 °C. As occurred in circuit 1 the temperature inside the

fruit was not highly affected by the refrigerator temperature presenting more linear. The temperatures inside the clamshell during storage was lower than the recorder inside the fruit.

Trunk temperatures

The temperatures registered in the trunks of 5 cars, all of dark colors, are represented in figure 20. The cars 1 was parked in garages during most of the study.

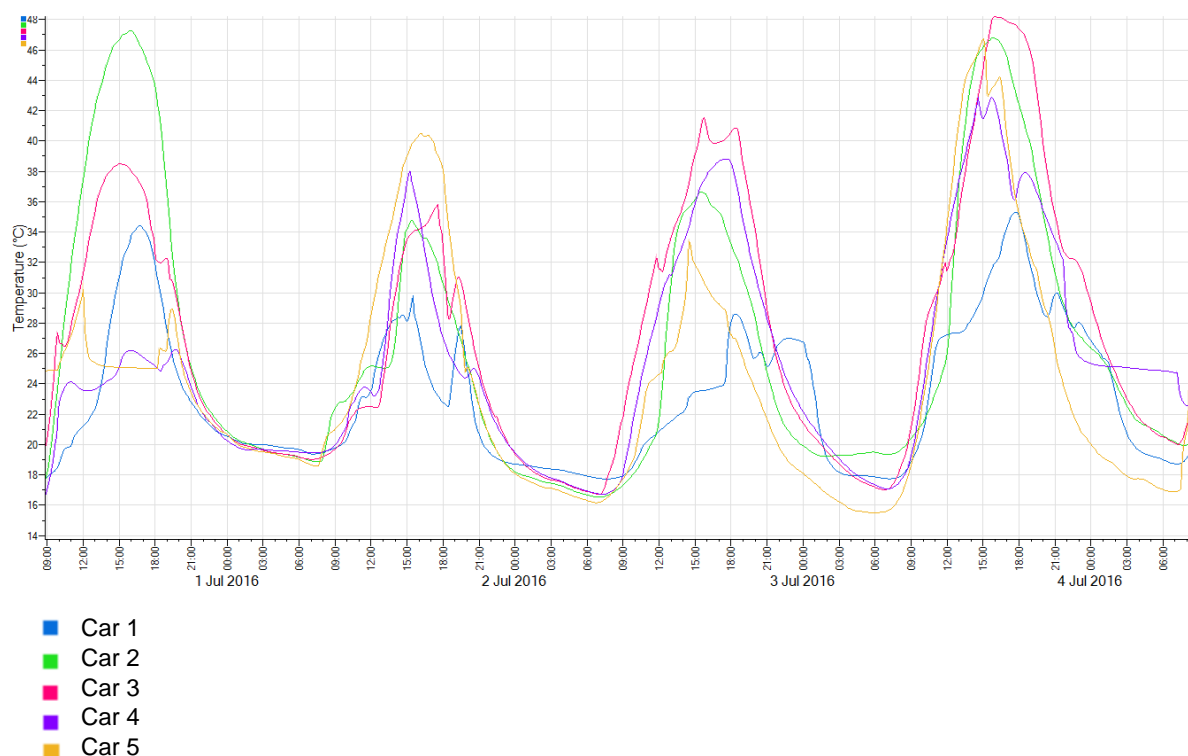


Figure 20 - Temperatures measured in 5 different personal cars trunks.

The temperature evolution pattern was similar in all cars regardless of the brand and model, but showing amplitude differences (table 11). The temperature range recorded was higher than 30 °C in some of the days. Cars parked in garages, Car 1, 4 and 5 in some periods of the study, recorded temperatures 10 °C lower when compared to ones parked outside. On 30th of June the temperature in the trunk of the car 2 reached 47.3 °C while the cars 4 and 5, which were parked in garages, registered at the same time temperatures of around 25 °C. The temperature of car 3 increased from 17 °C at 7:00 to 48.2 °C at 16:00 on the 3rd of July.

Table 11 - Minimum, maximum and mean temperature recorded in the vehicles trunks.

Vehicle	1	2	3	4	5
Minimum Reading (°C)	17.7	16.5	16.7	16.7	15.5
Maximum Reading (°C)	35.3	47.3	48.2	42.9	46.8
Mean Temperature (°C)	24.4	31.3	31.3	28.1	27.8

The maximum air temperature recorded during the study was 48.2 °C on the 3rd of July. The air temperature in Lisbon at that time was 36.6 °C according to Instituto Português do Mar e da Atmosfera (IPMA, 2016b), so the temperature inside the trunk was 11.6 °C higher when compared to the exterior temperature. On the other days the maximum temperature reached in the trunks were 47.3, 40.3 and 41.4 °C on days 1, 2 and 3, with a maximum exterior temperature registered, according to IPMA (2016b), of 24, 26.1 and 28.2 °C, respectively.

Consumer refrigerator temperature

The temperatures of 5 domestic refrigerators are represented in figure 21. The refrigerators 2 and 3 were not opened during the test period, being very clear the refrigeration cycles that oscillated in 3.5 °C each 70 minutes and 3 °C each 3 hours, respectively.

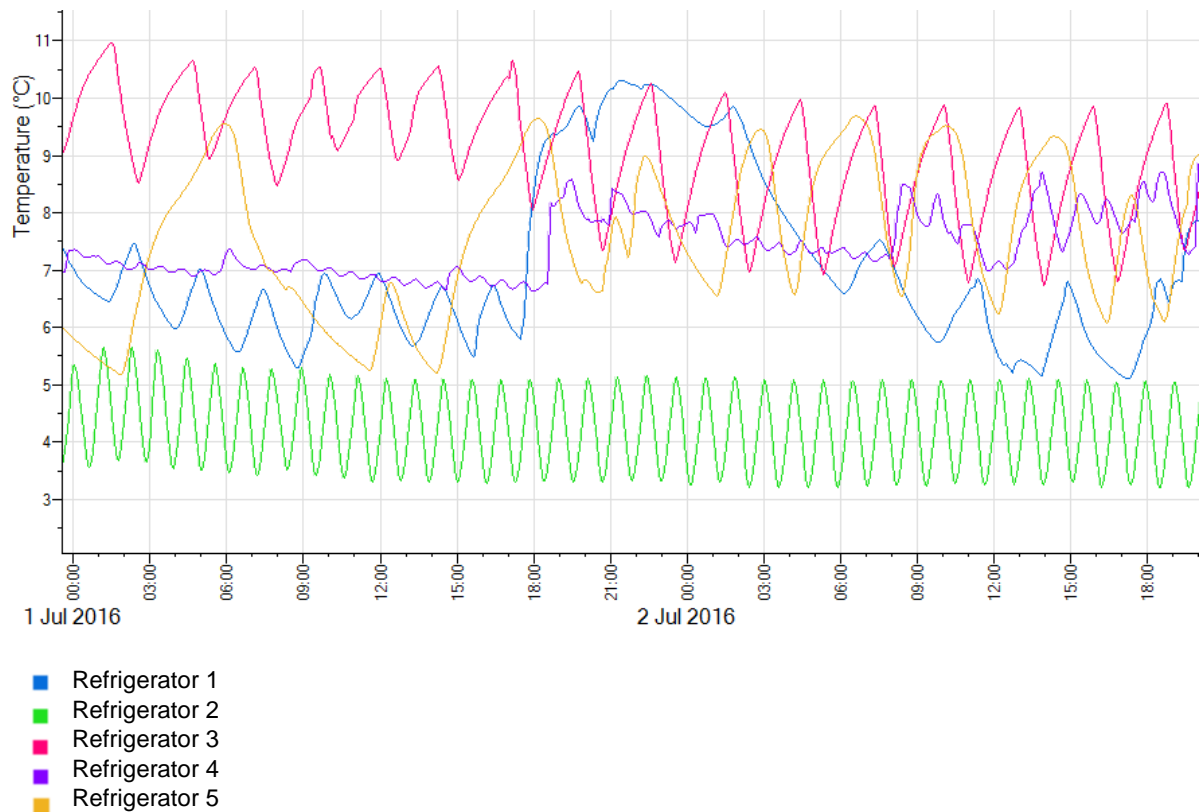


Figure 21 - Temperatures measured in 5 domestic refrigerators.

The refrigerator 4, with only 6 months of use, showed refrigerator cycles with less than one hour and amplitudes below 0.5 °C, the temperature oscillated between 7.0 and 7.5 °C during the first day (fig. 21). The remaining oscillated in cycles of 2 to 3 hours with amplitudes from 1.5 to 3.0 °C, but did not maintained the temperature around a constant mean value. The refrigerator 1, 4 and 5 showed no regular refrigerator cycles, registering a lot of temperatures

oscillations associated with door opening by the users. The door of the refrigerator 4 was open for 8 minutes on day 1 and was stocked with food which led to a rise of the temperature. With this increased load, the refrigerator could not maintain the same temperature range and registered an increase of 1 °C on his average temperature.

Were registered (table 12) oscillations of 5.2, 2.5, 4.3, 2.1 and 4.5 °C in refrigerators 1, 2, 3, 4 and 5, respectively. These oscillations may then lead to condensations in the clamshells what can lead to rot and mold development on the fruits.

Table 12 - Minimum, maximum and mean temperature recorded in the refrigerators.

Refrigerator	1	2	3	4	5
Minimum Reading (°C)	5.1	3.2	6.7	6.6	5.2
Maximum Reading (°C)	10.3	5.7	11.0	8.7	9.7
Mean Temperature (°C)	7.2	4.3	9.2	7.4	7.7

With the exception of the refrigerator 2, the temperatures recorded were very high to store strawberries which need temperatures close to 0°C in order to maintain their quality (Hardenburg et al., 1986). Storage fruits at these temperatures may lead to quality depreciation and rot development.

Part II – Temperature effects on strawberry quality and shelf-life

Mass loss

The mass loss (fig. 22), is associated mainly to the water loss by evaporation when the fruits are subject to different temperatures during storage.

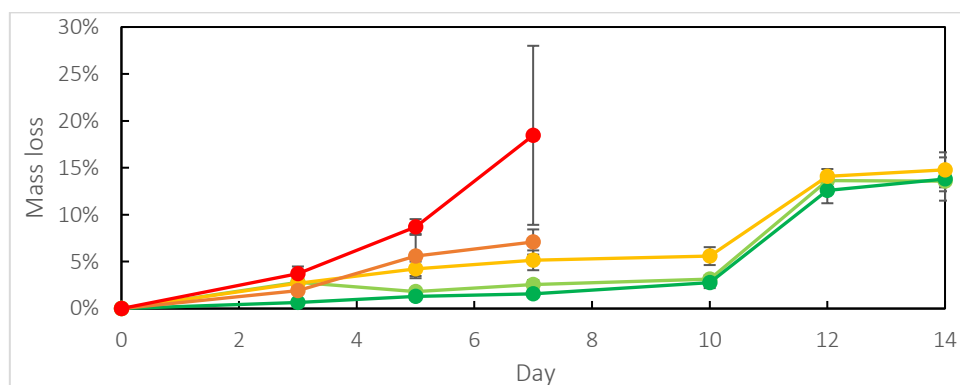


Figure 22 - Evolution of mass loss at different storage temperatures.

— 0°C — 5°C — 10°C — 15°C — 20°C

At 20 °C occurred the highest mass loss reaching 18.5 % on day 7, on the same day at 15, 10, 5 and 0 °C the mass loss registered was 7.1 %, 5.1 %, 1.6 % and 2.6 % respectively. The high standard deviation on day 7 at 20 °C was also due to the disintegration of some fruits that lead to juice runoff as a result of rot development.

A higher storage temperature led to a higher mass loss with the fruits stored at 0, 5 and 10 °C showing a similar tendency, with a similar outcome of approximately 14 % of mass loss.

According to Robinson et al. (1975) a mass loss of 6 % leads to unsaleable strawberries. That value was reached after 3, 5 and 10 days at 20, 15 and 10 °C respectively. At 0 and 5 °C the 6% water loss was only reached between days 10 and 12.

Fruit and calyx color

The evolution of fruit and calyx lightness, Chroma and hue degree are represented in figure 23.

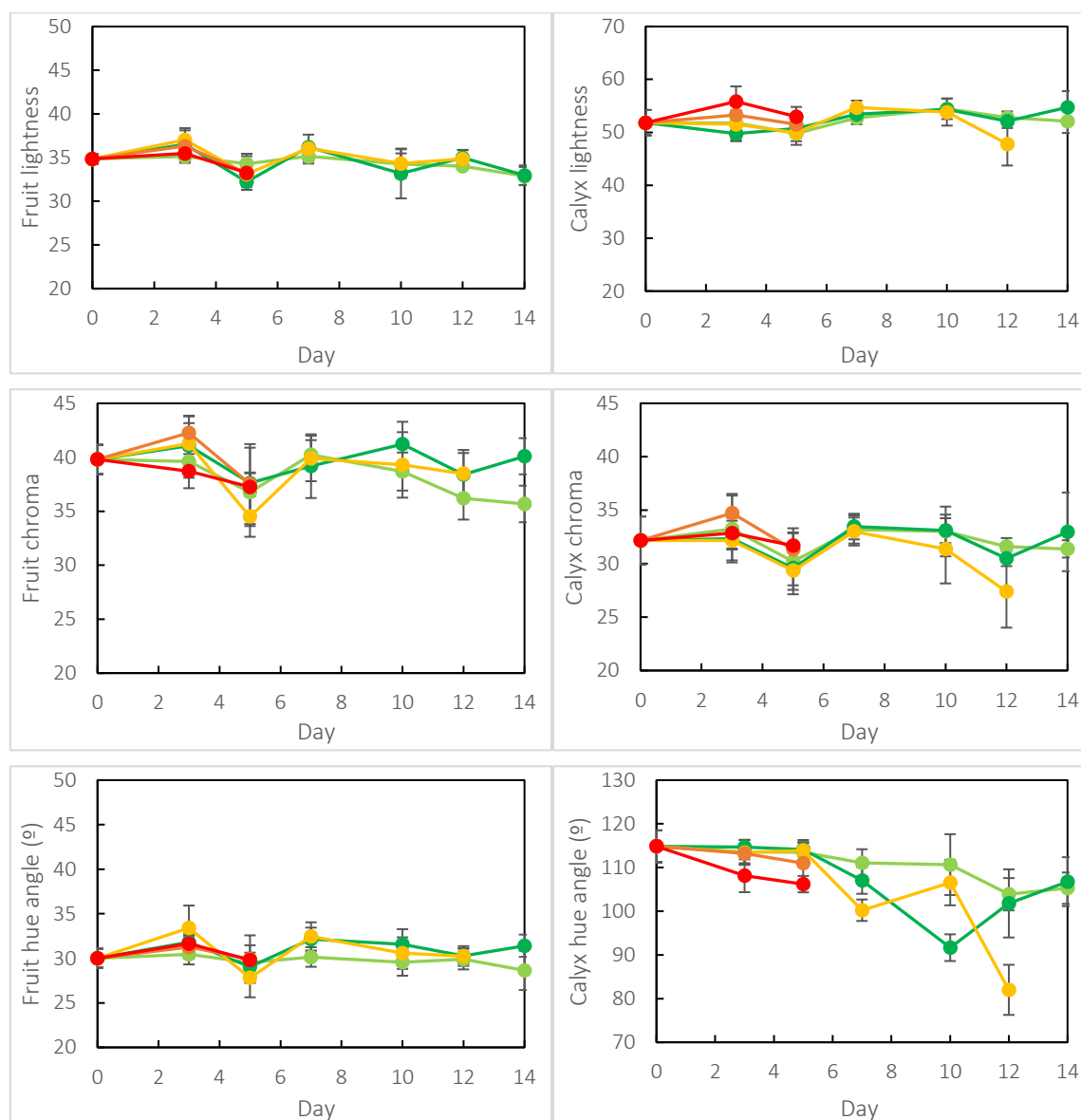


Figure 23 - Evolution of fruit and calyx lightness, chroma and hue angle at different storage temperatures.
 — 0°C — 5°C — 10°C — 15°C — 20°C

The color of the fruits did not undergo significant changes regardless of the time and temperature of storage. Although other authors had reported that the temperature and time of storage would affect the chroma and hue (Collins & Perkins-Veazie 1993) the results obtained show that the color of the fruits do not show changes large enough to allow visual differentiation by the consumer.

The calyx color, however, showed some differences according to the time and storage temperature. Fruits stored at 10 °C showed a reduction of the lightness, chrome and hue angle, which indicates darkening and yellowing. Still the calyx of fruits stored at 0 and 5 °C showed no significant differences between them but a slight yellowing could be observed.

Firmness

At 0 and 5 °C the fruits showed a slight decrease in their firmness (fig. 24a) from the initial 0.83 ± 0.14 N to 0.63 ± 0.11 and 0.71 ± 0.13 N respectively. The differences however were not significant.

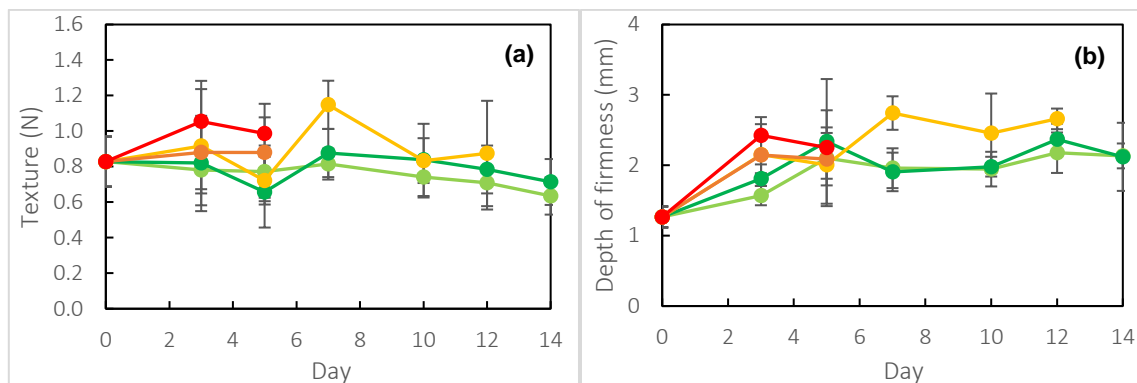


Figure 24 - Evolution of fruit (a) pick of firmness and (b) depth of maximum firmness at different storage temperatures. —●— 0°C —●— 5°C —●— 10°C —●— 15°C —●— 20°C

The depth of the peak of force (fig. 24b) detected increased in all the temperatures tested which indicates that the exterior part of the fruit suffered a high decrease in firmness. With the peak of force increasing in depth from 1.27 ± 0.15 mm to 2.13 ± 0.18 , 2.12 ± 0.48 , 2.66 ± 0.15 , 2.09 ± 0.37 and 2.25 ± 0.28 mm at 0, 5, 10, 15 and 20 °C respectively in the last day tested.

Several authors reported that the fruits lose firmness with storage and that softening rate is higher at higher temperature (Nunes and Emond, 1999; Collins and Perkins-Veazie, 2003; Nunes 2008; Lai, 2010). Yet the results obtained do not show a reduction in the firmness of the fruit for itself but a reduction of the firmness of the surface of the fruit. Most of the studies measured the firmness by deformation which may show a decrease in firmness since the exterior part of the fruit when compressed collapses leading to the results reported. The fruit remains firm inside only showing a reduction of firmness on the first mm of the fruit.

Soluble solid content and titratable acidity

The evolution of soluble solid content and titratable acidity are represented on figures 25 and 26, respectively.

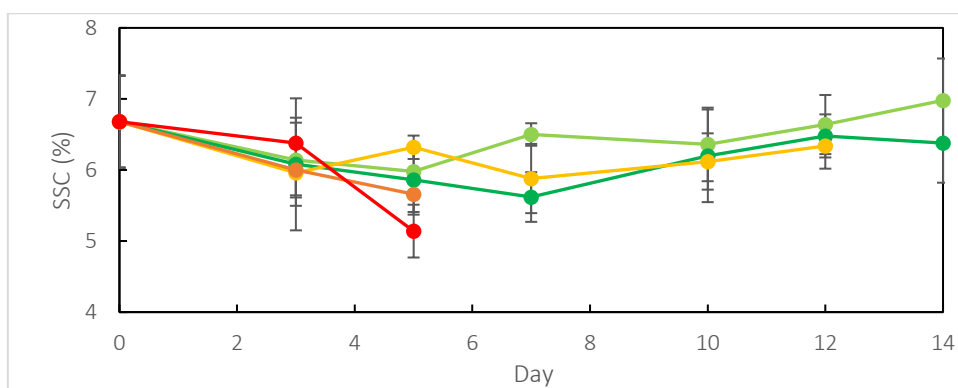


Figure 25 - Evolution of soluble solid content at different storage temperatures.

— 0°C — 5°C — 10°C — 15°C — 20°C

As observed by Shin et al. (2007) at 0 °C was observed a slight increase on the soluble solid content (SSC) from $6.68 \pm 0.65\%$ to $6.98 \pm 0.59\%$. Fruits stored for 5 days at 20 °C showed a reduction from 6.68 to 5.14 %.

However, in general, the results obtained show no significant differences on the SSC of the fruits regardless of the temperature, unlike reported in the literature that observed a reduction of the SSC of the fruits (Ayala-Zavala et al., 2004; Nunes et al. 2006).

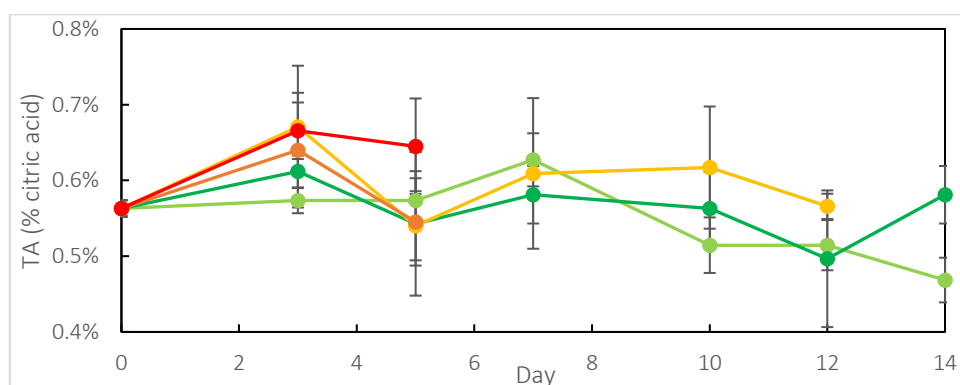


Figure 26 - Evolution of titratable acidity at different storage temperatures.

— 0°C — 5°C — 10°C — 15°C — 20°C

The fruits stored at 0 °C showed a slight decrease on the TA from $0.56 \pm 0.01\%$ to $0.47 \pm 0.03\%$. Yet, as previously reported by Cordenunsi et al. (2003) and Ayala-Zavala et al. (2004) there were observed no significant changes on the titratable acidity (TA) that may be perceived by the consumer.

Sensorial analysis

Figure 27 indicates the changes in sensory attributes during shelf-life of strawberry.

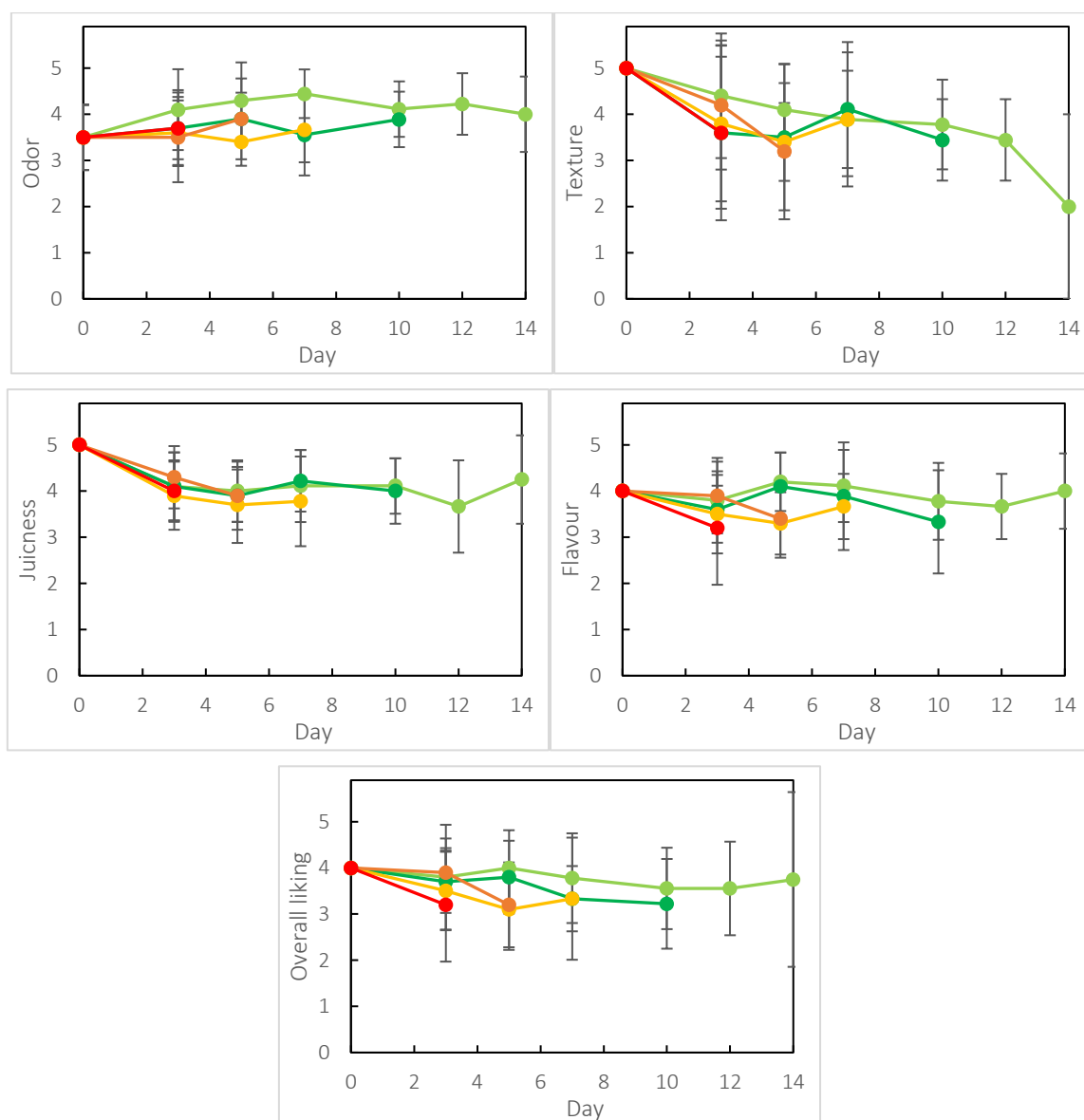


Figure 27 - Evolution of Sensorial perception of odor, texture, juiciness and flavor and overall liking at different storage temperatures. —●— 0°C —●— 5°C —●— 10°C —●— 15°C —●— 20°C

Changes observed in the odor of fruits during shelf-life were not significant regardless of the temperature. The average value of the odor was 3.9, which represents according to the tasting sheet 'fresh fruits with some aroma'. Yet, fruits stored at 0°C tended to have higher ratings throughout the study than the fruits stored at higher temperatures, with an average 4.2 score.

Initial texture was rated as 5.0 ± 0.0 with the panel considering that fruits had the 'perfect texture' just after harvested. The texture rating tended to decrease afterwards at all temperatures, however this decrease on the rating was mostly due to a perceived increase in the firmness with most of the panelists scoring fruits as hard and slightly hard. This could be due to an increase in pectin viscosity (the gelling behavior) as Shin et al. (2007) reported.

Fruits juiciness was rated 5.0 ± 0.0 on day 0 indicating that the entire panel considered the fruits as 'very juicy'. There were noticed no differences on fruits juiciness after day 3. The scored

attributed to fruit juiciness decreased to an average 4 indicating that the panel considered the fruits as juicy regardless of the storage period and temperature. The weight loss that occurred was not perceived by the panel.

Fruits flavor was considered as 'fairly good taste' on day 0. There were no significant changes in consumer perception according to time and temperature of shelf life. The average score was 3.7 indicating that the panel considered the flavor of the fruit between 'slight taste' and 'fairly good taste'.

The overall liking of the fruits after harvest was rated as good from the entire panel. The rating attributed to the overall liking was very similar to the flavor indicating that the flavor is the attribute that the consumer when evaluating the fruits takes most in account. On day 14 the evaluation of the fruits stored at 0 °C showed a high standard deviation (3.75 ± 1.89) with some panelists considering the fruits as 'very good' and others as 'poor' or even 'unacceptable'. This may be due to the damages development and the decrease in the firmness rating leading some panelists to reduce their overall liking.

Damage development

The real problem that the strawberry supply chain faces after harvest is the losses mainly associated with bad temperature management. The type of loss causes established for the strawberry (fig. 28) was based on the symptoms and the genesis essential aspects for the implementation of corrective measures. Were considered two types of mechanical damages and two types of pathological symptoms which, as will be seen, may evolve from one to another.

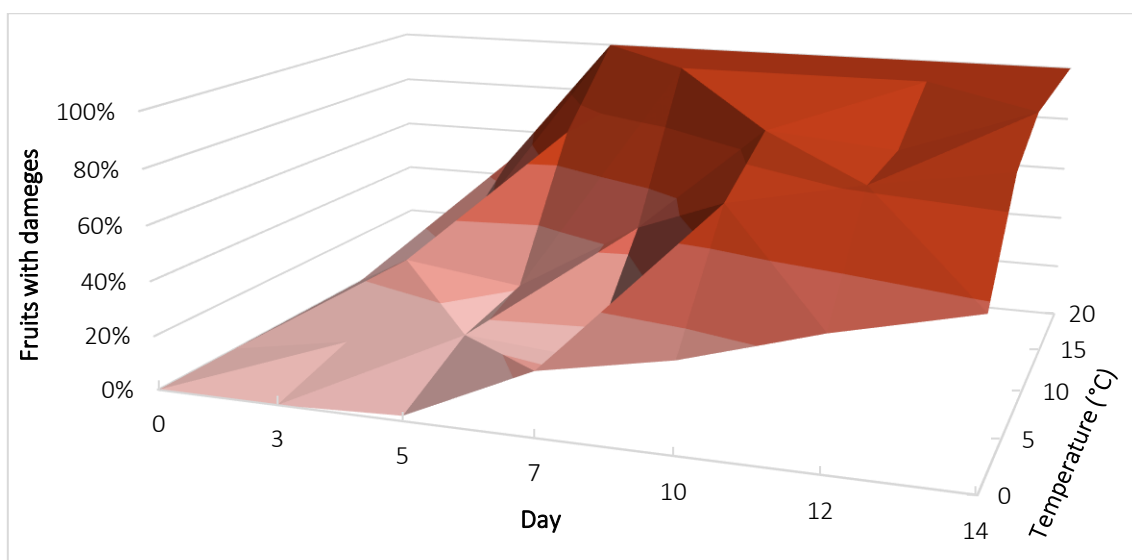


Figure 28 - Evolution of fruits with damages at different storage temperatures (1st study).

0%-20% 20%-40% 40%-60% 60%-80% 80%-100%

The initial batches of fruits were practically free from visible damages. However, the damages became evident soon after harvest and the proportion of fruit with some types of damage increased with increasing time and storage temperature (fig. 28 and 29). However, the temperature had a greater influence on the increased incidence of damages than the storage time. After 5 days at 20 °C 100 % of the fruits were damaged yet after 14 days at 0 °C only 57 % of the fruits showed damages.

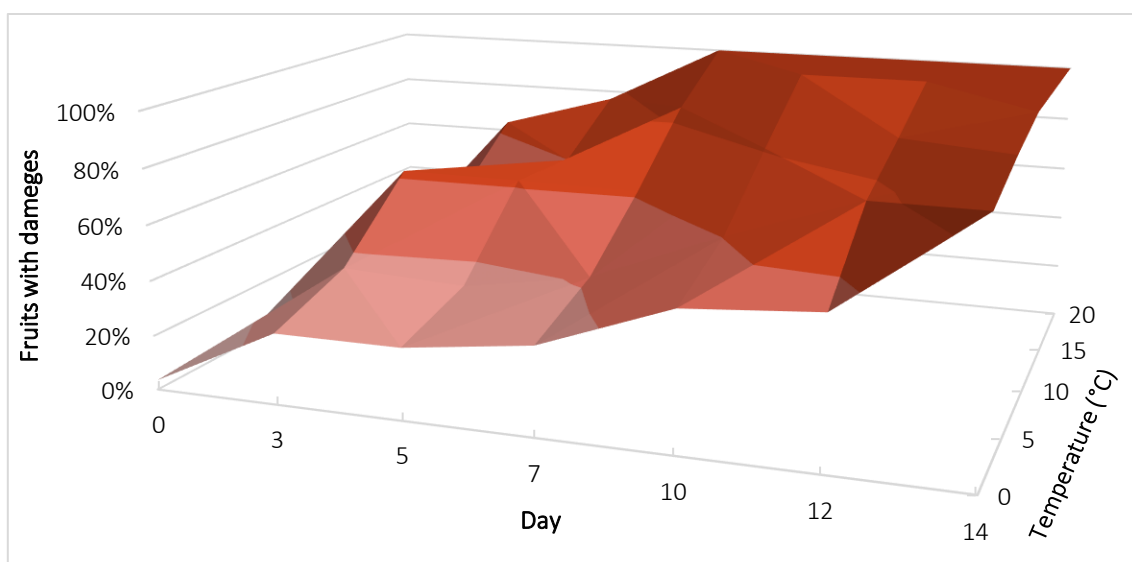


Figure 29 - Evolution of fruits with damages at different storage temperatures (2nd study).

0%-20% 20%-40% 40%-60% 60%-80% 80%-100%

On the 2nd study the damages stated to appear earlier when compared to the 1st study, especially at lower storage temperatures. On day 3 at a temperature of 0 °C the proportion of

damaged fruits were 0 and 25.9 % for the 1st and 2nd study, respectively. This could have happened due to the differences associated to the variety or due to the temperatures when harvested, since the 1st study was done in April and the 2nd in July with mean maximum temperatures of 19.8 and 34.6 °C, respectively (IPMA, 2016a; IPMA, 2016b).

The pattern of damages progression shows that the occurrence and incidence proportion can rise very rapidly at temperatures above 10 °C, making very probable that these damages may occur in stores and at consumers' houses after purchase if not taken into account the storage temperature.

Figure 30 shows the evolution of fruits with damages with the standard deviation associated. In both studies the damages development appeared first at higher the temperature.

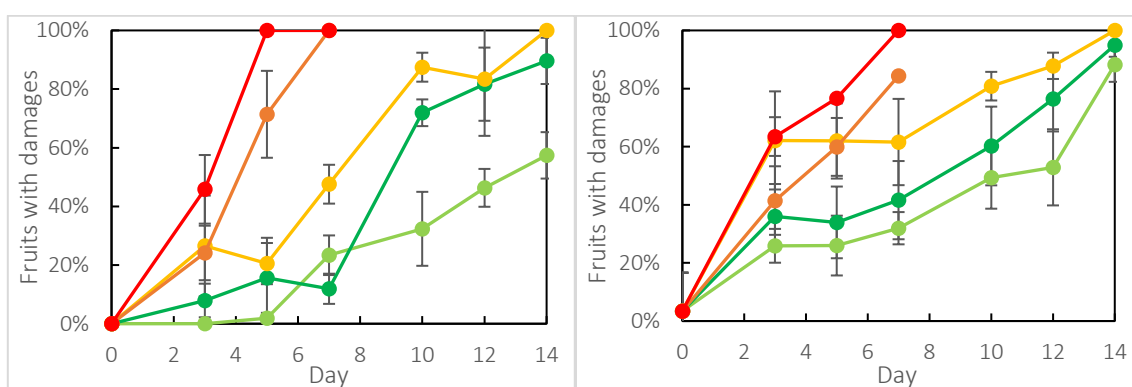


Figure 30 - Evolution of fruits with damages at different storage temperatures on (a) 1st and (b) 2nd study.
 — 0°C — 5°C — 10°C — 15°C — 20°C

According to Shin et al. (2007) storing strawberries at 10 °C for 4 days resulted in no difference in their quality, however, the results obtained show differences at day 3 from 0 to 26.5 % of damaged fruits and from 25.9 to 62.2 % of damaged fruits from 0 to 10 °C in the 1st and 2nd study, respectively.

Takeda et al. (1990) reported that after 2 days of storage at 18 °C more than 35 % of the fruits showed damages. On day 3 for fruits stored at 20 °C the percentage of damaged fruit were 45.8 and 63.5, for study 1 and 2, which is consistent and even higher with the reported by Takeda et al. (1990).

On annex II and III are photographs that allow to understand in a visual way the evolution of the damages on the 2nd study according to temperature and storage period.

Types of damages

If in the point of view of quantifying the losses was considered the totality of the damaged fruits, not concerning about their type and genesis, these aspects become essential to implement

effective corrective measures. On figures 31 and 32 are represented the evolution of damages by type.

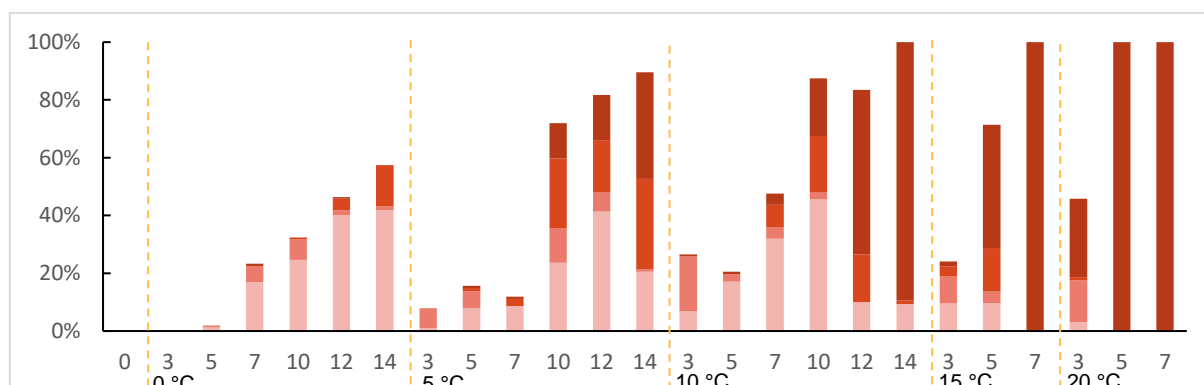


Figure 31 - Evolution of damages by type at different storage temperatures (1st study).

■ Dry bruises ■ Wet bruises ■ Rot without visible hyphae ■ Rot with visible mycelium

The bruises become evident on day 3 to temperatures higher or equal to 5 °C and after 5 days at 0 °C, with only 1 % of affected fruit; at 10, 15 and 20 °C, rots appeared on day 3 and at 5 °C on day 5. At 0 °C only after 7 days was observed occasional occurrence of visible mycelium (1 in 145 fruits) and did not increased during storage. After 14 days fruit stored at 0 °C showed no visible mycelium. After 7 days losses due to rotting, with and without visible mycelium were 0.8, 3.2, 11.7, 100 and 100 % to 0, 5, 10, 15 and 20 °C respectively. The clamshells made up unmarketable after 3 days at 20 °C, 5 days at 15 °C, 7 days at 10 °C, 10 days at 5 °C and 12 days at 0 °C.

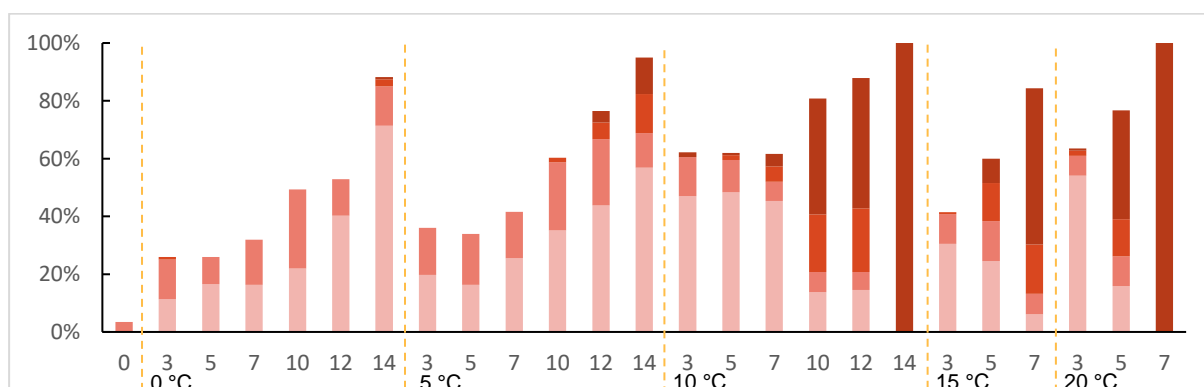


Figure 32 - Evolution of damages by type at different storage temperatures (2nd study).

■ Dry bruises ■ Wet bruises ■ Rot without visible hyphae ■ Rot with visible mycelium

On the harvest day (day 0) already 3 % of the fruits showed wet bruises. On day 3 the percentage of fruits affected by bruises were 24, 36, 61, 40 and 62 % at 0, 5, 10, 15 and 20 °C, respectively, which represents a higher incidence when compared to the 1st study. At 10,

15 and 20 °C, rots also appeared on day 3, however, at 5 °C rots were only visible on day 10. At 0 °C after 14 days 1 % of the fruits presented rot development without visible hyphae.

Over time, it's visible a decreasing tendency in bruised fruits and an increasing incidence of fruits showing rot development with and without visible mycelium (fig. 33).

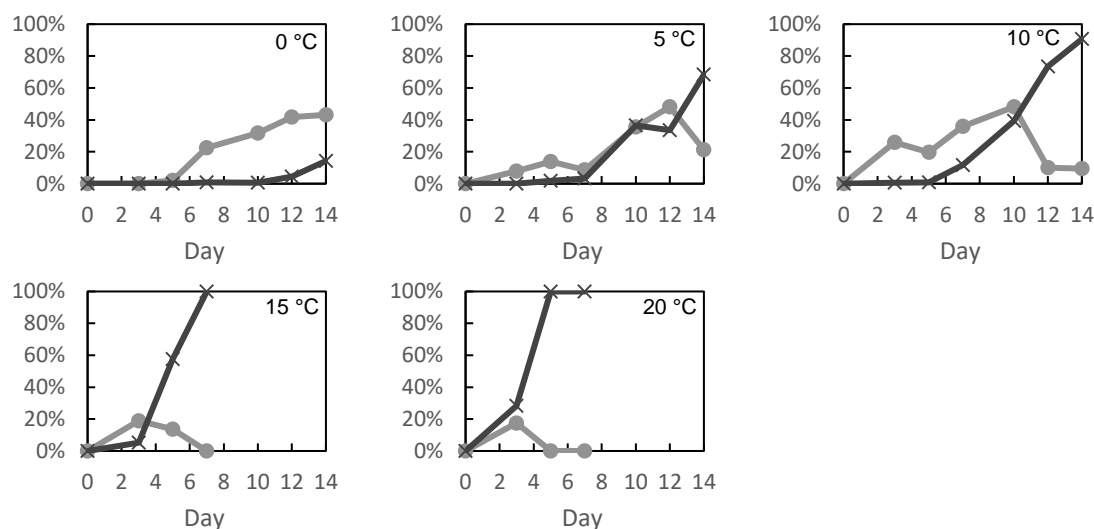


Figure 33 - Evolution of the incidence of bruises and rots, as a percentage of total fruit at different temperatures depending on the storage time, 1st study.

—●— Dry and wet bruises —×— Rot with and without visible mycelium

The percentage of fruits showing bruises increased initially at all temperatures, but during the storage period the bruises tended to progress to rots. Note that we are facing latent damage (Almeida, 2005) not evident in the initial batch, but which become visible and evolve very quickly. Mechanical damage caused by compression during harvest and subsequent handling or vibration during selection operations, transportation and transfers need to be minimized. The fact that there are not visible damages at the time of choice is not proof of his absence. Additionally, *Botrytis cinerea* infection predominantly occurs during senescence of the petals, so that reduction of latent infections and inoculum load needs to be achieved in the field. Mechanical damage are also penetration doors and favor infection and disease development and can be colonized by fungi that will later express in the supply chain especially when temperatures rise at the retail or consumer level.

Part III – Estimation of quality depreciation in the strawberry supply chain

The objective of this work was to develop a way to estimate the quality depreciation at which the strawberries could be subject according to their transport and storage temperatures.

In table 13 are represented the ATT for each temperature and storage time tested. To the storage ATT it was added 113 °C h that represents the ATT from harvest until the arrival to the laboratory, assuming the values calculated for circuit 1 that correspond to the fruits supplier for the study.

Table 13 - Accumulated time-temperature (ATT) and mean of the percentage of damaged fruits (%df) from both studies for each temperature and storage time.

Days (hours)	1 °C		5 °C		10 °C		14 °C		20 °C	
	°C h	%df	°C h	%df	°C h	%df	°C h	%df	°C h	%df
3 (72)	185	13%	473	22%	833	44%	1121	33%	1553	54.7%
5 (120)	233	14%	713	25%	1313	41%	1793	66%	2513	88.3%
7 (168)	281	28%	953	27%	1793	55%	2465	92%	3473	100.0%
10 (240)	353	41%	1313	66%	2513	84%	3473		4913	
12 (288)	401	50%	1553	79%	2993	86%	4145		5873	
14 (336)	449	73%	1793	92%	3473	100%	4817		6833	

No absolute correlation was found between the ATT and the percentage of damaged fruit. For example, fruits stored for 14 days at 1 °C and for 3 days at 5 °C had an ATT of 449 and 473 °C h and 73 and 22 % of damaged fruits, respectively, which represents a large difference. This is due to the fact that the temperature has a higher influence in the damage development than the storage time.

In table 14 are represented the ATT from circuit 1 and 2 supply chain, 'last mile' period and the total ATT.

Table 14 - Accumulated time-temperature (ATT) of the entire circuit 1 and 2.

	Circuit 1 (6 days, 13 hours)	Circuit 2 (4 days, 22 hours)
ATT	(°C h)	(°C h)
Supply chain	502.3	588.8
'Last mile'	669.9	352.6
Total ATT	1172.2	941.4

Since the temperature and time of storage do not have the same weight to estimate the damages one should first assess the duration of the entire circuit. Then estimated the percentage of damaged fruit according to a linear regression for the results obtained for that same time.

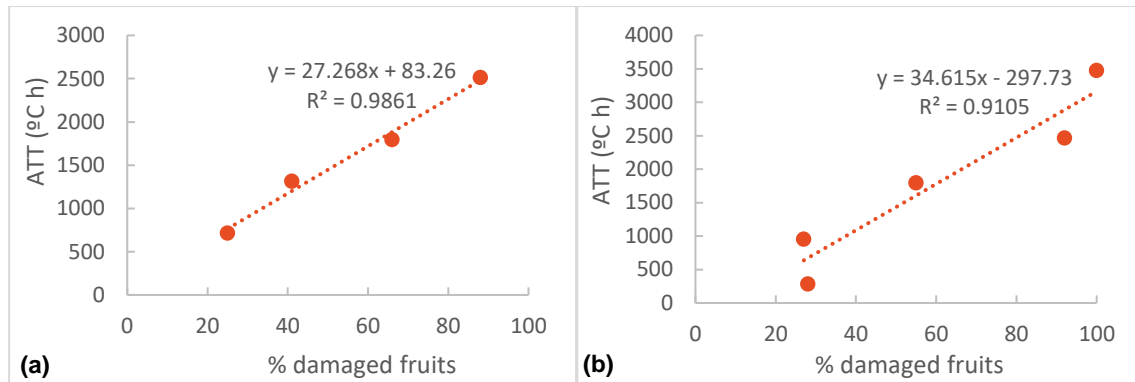


Figure 34 – Linear regression of the ATT and percentage of damaged fruits for (a) 5 and (b) 7 days of storage.

Circuit 1 took almost 7 days and had an ATT of 1172.2 °C h which may have led to a percentage of damaged fruits of 42%. Circuit 2 only took close to 5 days and had an ATT of 941.4 °C h leading to an estimated 35.8% of fruits with damages. Although there has been a difference of almost two days between circuits they both lead to similar estimations of damaged fruits.

Conclusion

The factors determining strawberries quality in the supply chain are the mechanical damages and pathological infections, which quickly evolve even if the symptoms are not evident at harvest. The physicochemical and sensory characteristics are essentially determined at the time of harvest and the effects of their subsequent post-harvest evolution from the point of view of full quality management in the chain does not overlap the effects caused by mechanical damages and rots. The rapid evolution of the damages at temperatures above 0 °C shows that management of the temperature in the entire supply chain is fundamental, even at the end in retailer and consumer level. The analysis of the causes and evolution of symptoms of losses reveals that the initial characteristics, the latent infections, the level of inoculum and mechanical damage at harvest, packaging and transport are determining the satisfaction of retailers and consumers. The temperature has a higher impact on the development of damage than the storage time, with retailers being able to increase selling time in 3 times if they choose to display the fruit in refrigerator areas instead of ambient temperature. If fruits were stored under refrigerator conditions (5 °C) instead of in store ambient temperature areas (20 °C) an increase in 7 days on the shelf life could be possible.

Decay was the major cause of quality loss during shelf-life of strawberry with the physicochemical and sensory variables assessed not showing significant differences, imperceptible to the sensorial panel. The major cause of loss and quality depreciation is the rot development that is mainly affected by the storage temperature. The development of visible mycelium only occurred at temperatures above 5 °C with special focus in fruit stored at 15 and 20 °C that started to be evident after 3 days.

The study of temperatures in the supply chain of two commercial circuits showed that exist in the same pallet temperature gradients that exceed the 10°C; fruits may be exposed to temperatures above 35 °C; and that the fruits remain for extended periods in unfavorable conditions above 10 °C. The temperatures recorded in the top of the pallet allowed to understand that occur a lot of breaks in the temperature of the supply chain. However, in the middle and bottom of the pallet these changes on the temperature, when arise for a short period are not experienced, this may be due to the “protection” to the temperature transfer from the secondary packaging both during cooling periods and during unwanted rises of the temperature. Could be advantageous the use of a covering in order to reduce the abrupt changes in the temperature that fruits at the top of the pallet are subject.

Were accumulated in supply chain of both circuits temperatures of 502.3 and 588.8 °C h, between harvest and purchase by the consumer, with a large contribution from the store display with 273.1 and 281.2 °C h.

In the 'last mile', from purchase and during storage at the consumer refrigerator were accumulated 669.9 and 352.6 °C h, which indicates that this last step of the supply chain can have such a big importance on the quality of the strawberries, that may lead to the whole temperature maintenance efforts made until then to be wasted. The conditions of 'last mile' supply chain are conducive to high percentage of losses, leading to high depreciation of quality in the consumer household.

The temperatures in the 'last mile', in particular, in cars trunks and domestic refrigerators may lead to higher damages development than in the entire supply chain. The trunks of private vehicles reached values 20 °C higher than the outside temperature and absolute values close to 50 °C. The consequences of exposure of strawberries to these values, depending on the period, is not quantified. In domestic refrigerators were recorded temperature fluctuations greater than 5 °C. The temperatures in the refrigerators may be insufficient to maintain the quality of strawberries and storage for long period in these conditions may lead to rot development and consequently their waste from the consumer.

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Annexes

Annex I – Tasting Sheet

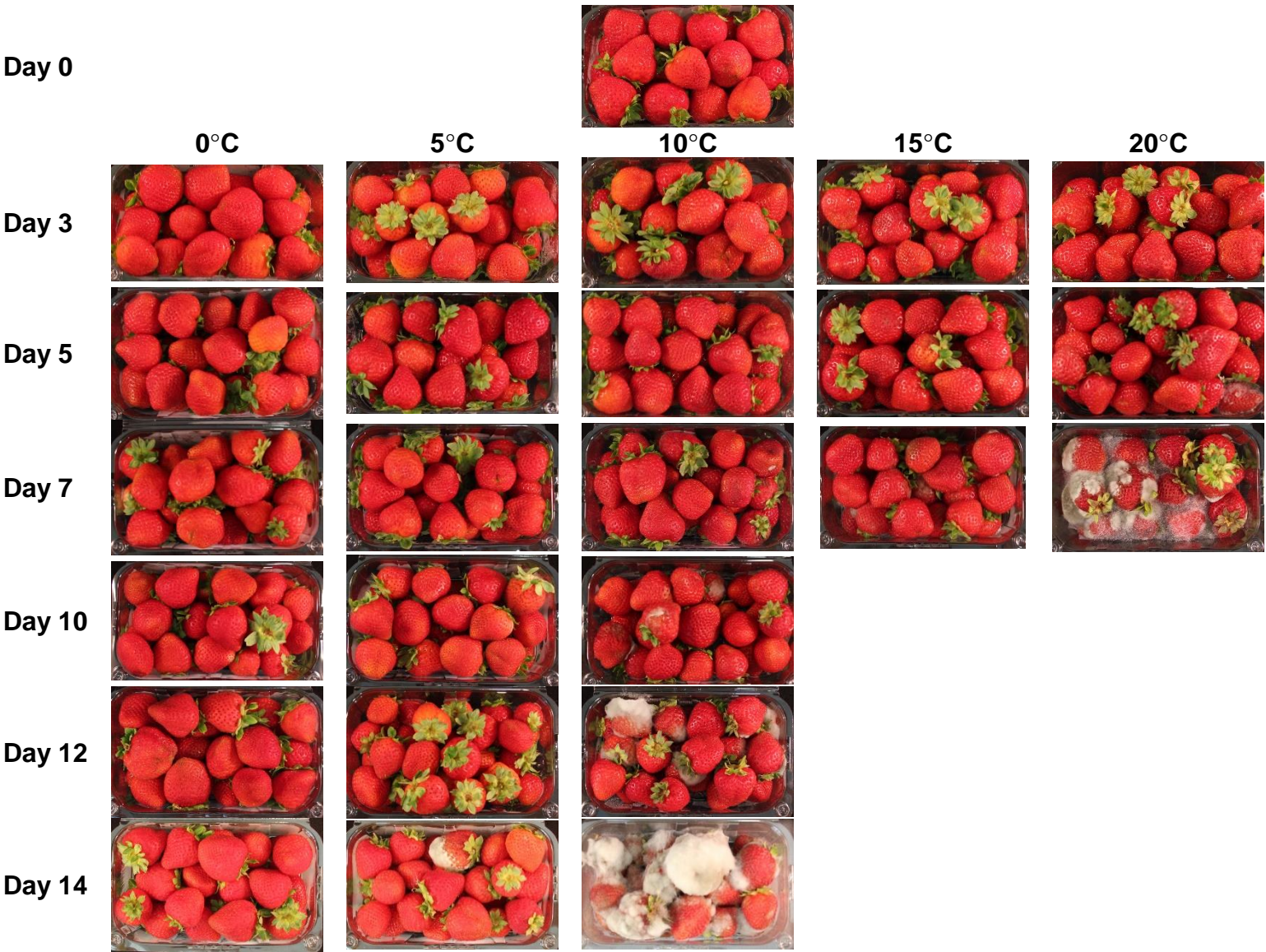
Product

Date

Criteria	Samples					
	1	2	3	4	5	6
Odour						
Fresh, good aroma						
Fresh, some aroma						
Little or no aroma						
Slight off-aroma						
Intense off-aroma						
Texture						
Hard						
Slightly hard						
Correct						
Soft						
Very soft						
Juiciness						
Very juicy						
Juicy						
Slightly juicy						
Slightly dry						
Dry						
Flavour						
Good balance (sugar: acid)						
Fairly good taste						
Slight taste						
Poor taste, or some off-flavours						
Bad off-flavours						
Overall						
Very good						
Good						
Acceptable						
Poor (probably would not buy)						
Unacceptable (definitely not buy)						

Comments:

Annex II – Photographs of the clamshells per temperature treatment



Annex III – Photographs of 5 fruit per temperature treatment (same fruits for each temperature)

